WASH123D:

A Numerical Model of Flow, Heat Transfer, and Salinity, Sediment, and Water Quality Transport in WAterSHed Systems of 1-D Stream-River Network, 2-D Overland Regime, and 3-D Subsurface Media (WASH123D: Version 2.0)

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WASH123D: Hydrology and Hydraulics

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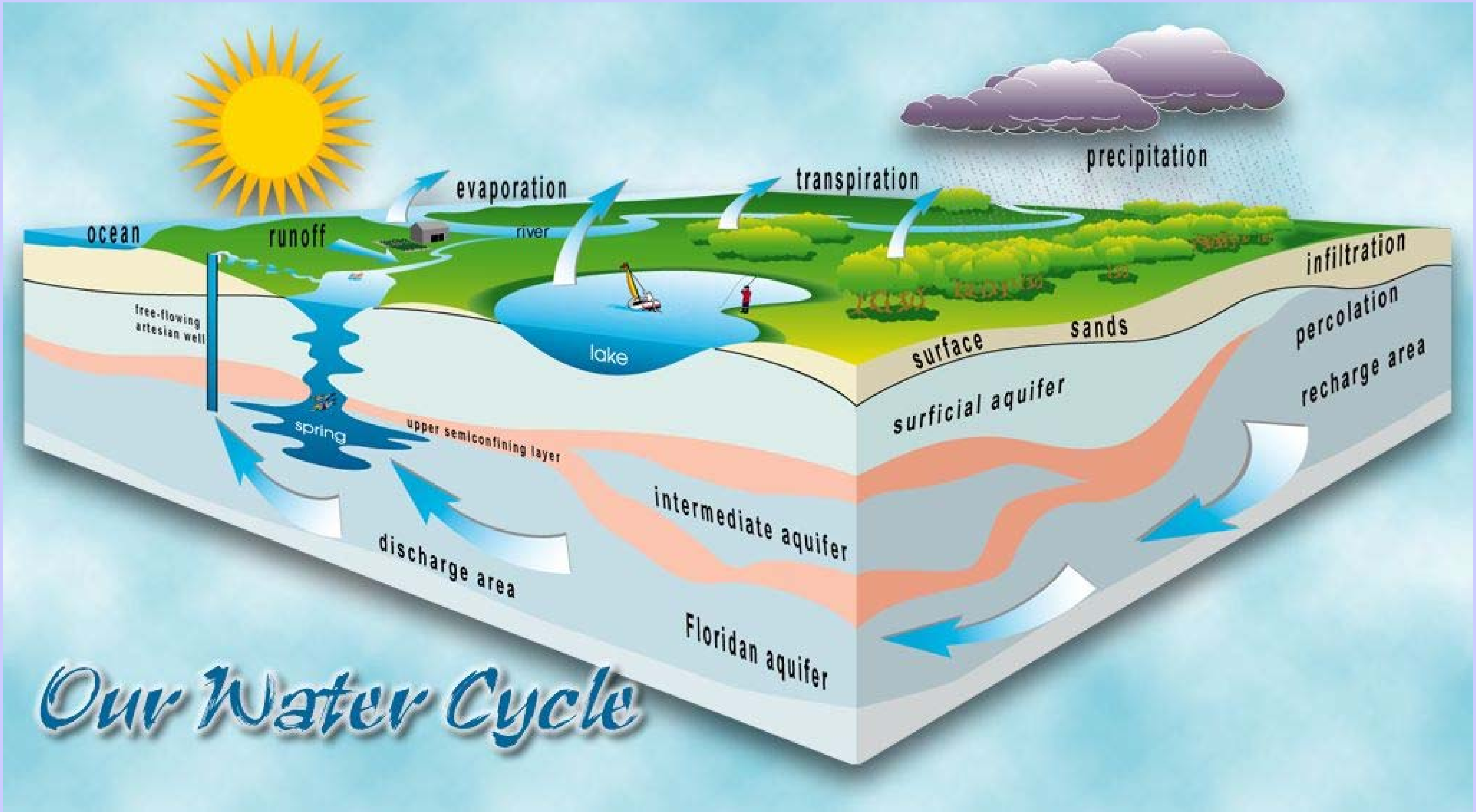
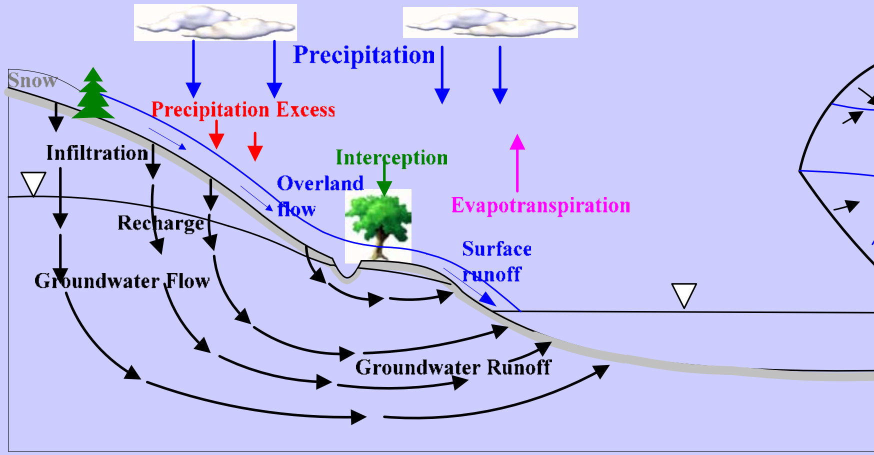
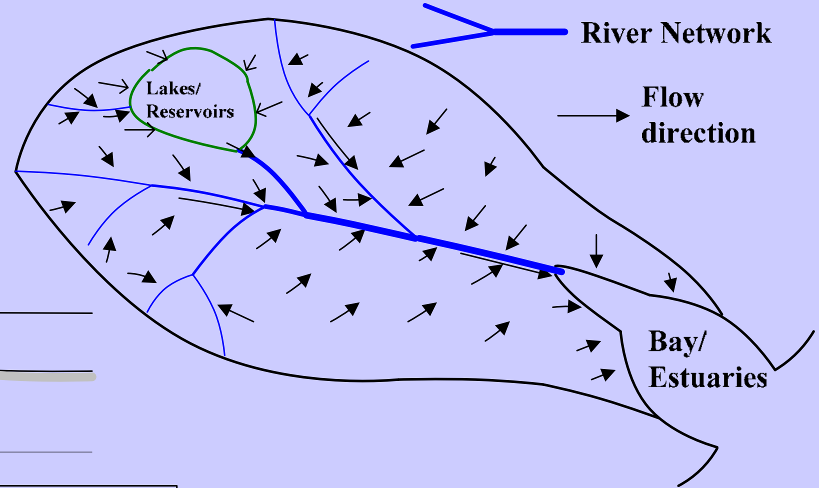
Water and Biogeochemical Cycles on Watershed Scales in Florida

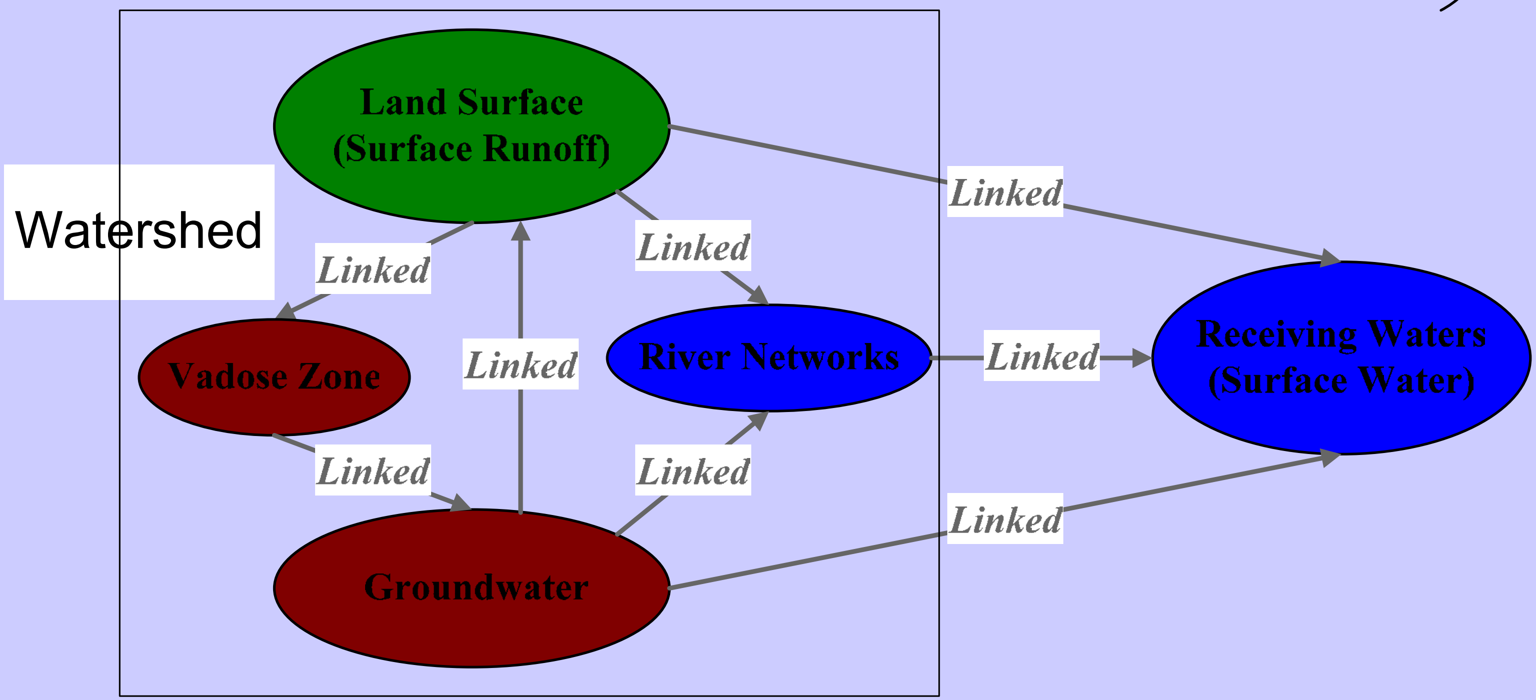


Integrated Watershed Models

- Linked Models
  - External link
  - Internally one-way link or two-way link
- Partially Linked and Partially Coupled Models
  - River-Subsurface Coupled
  - Overland Land-Subsurface Coupled
- Coupled Models
  - Ad hoc coupled with the linkage terms
  - Rigorously coupled with continuity of fluxes and state variable


Precipitation
Snow
Precipitation Excess
Infiltration
Interception
Overland flow
Evapotranspiration
Recharge
Surface runoff
Groundwater Flow
Groundwater Runoff


River Network
Flow direction
Lakes/ Reservoirs
Bay/ Estuaries


Watershed
Land Surface (Surface Runoff)
Vadose Zone
River Networks
Groundwater
Receiving Waters (Surface Water)
Linked
Linked
Linked
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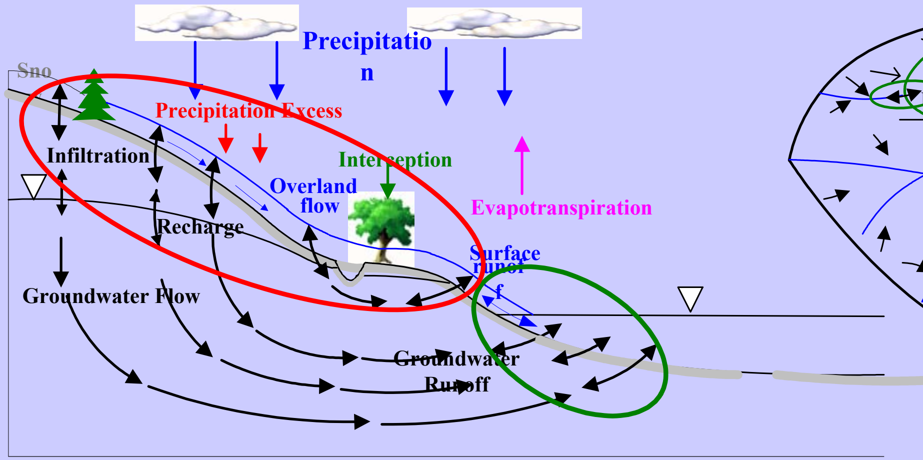
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Overland
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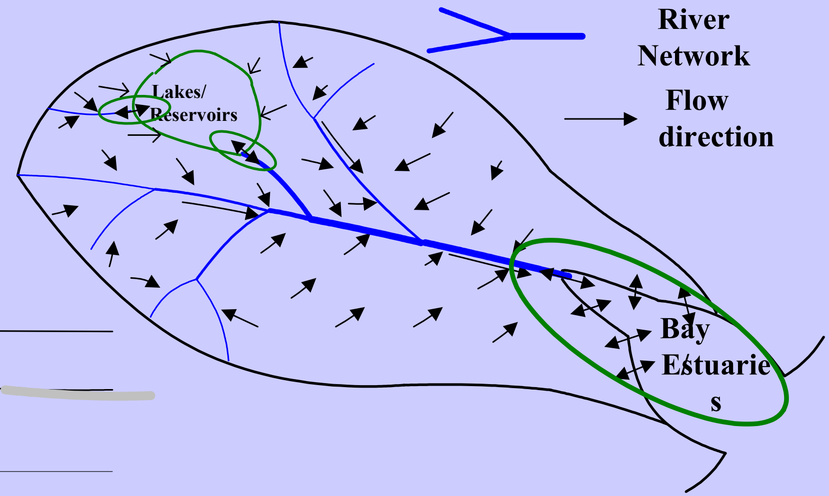
Groundwater Flow
Groundwater
Runoff


River
Network
Flow
direction
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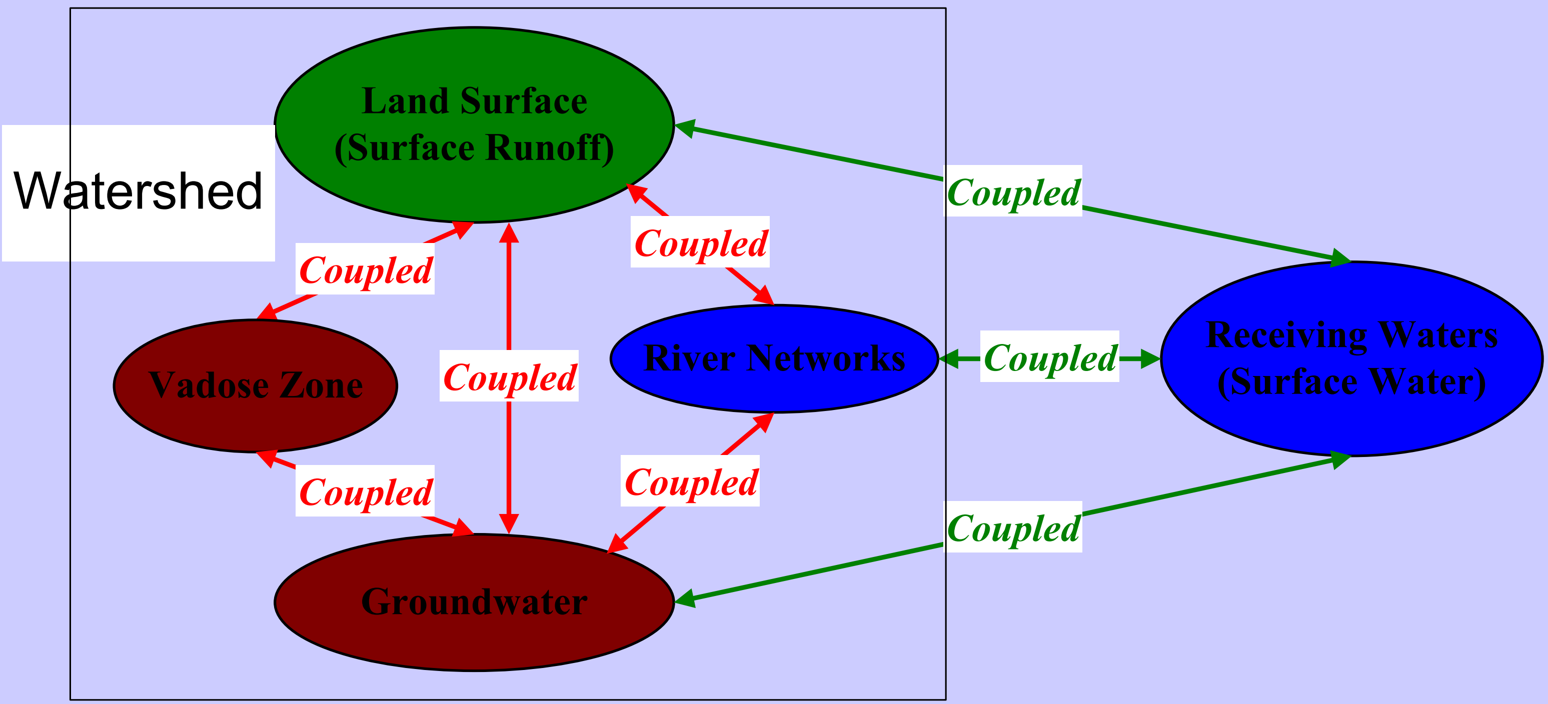
Watershed
Land Surface
(Surface Runoff)
Vadose Zone
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Receiving Waters
(Surface Water)
Coupled
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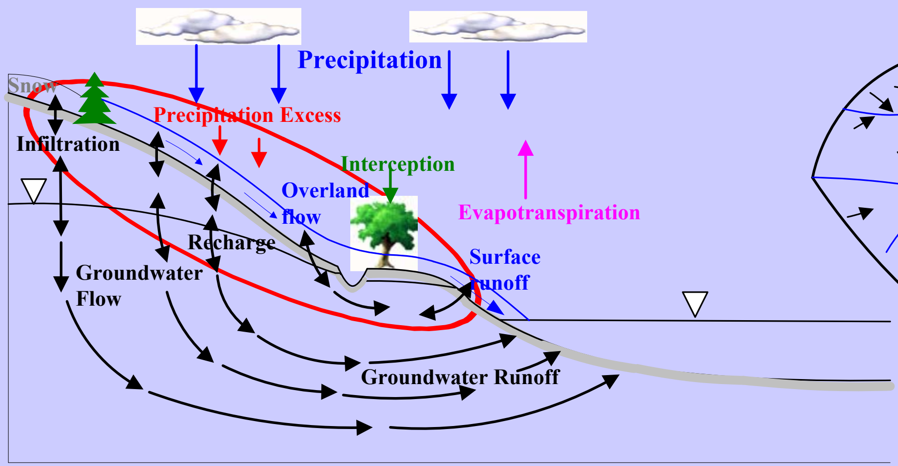
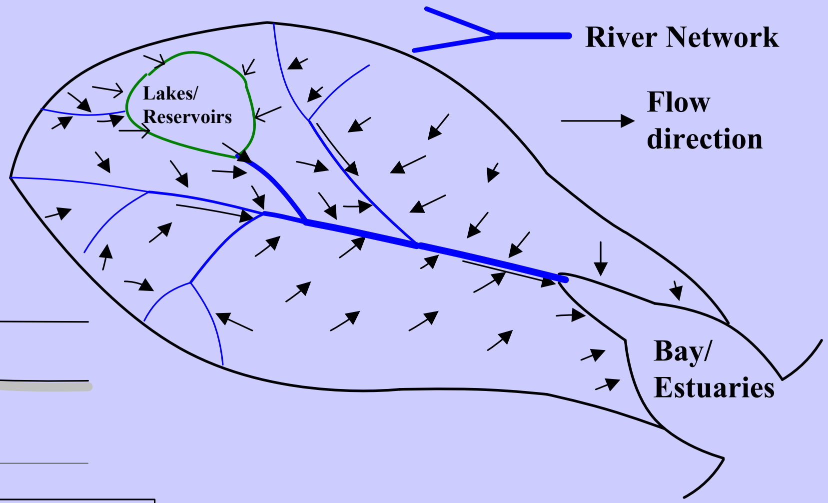
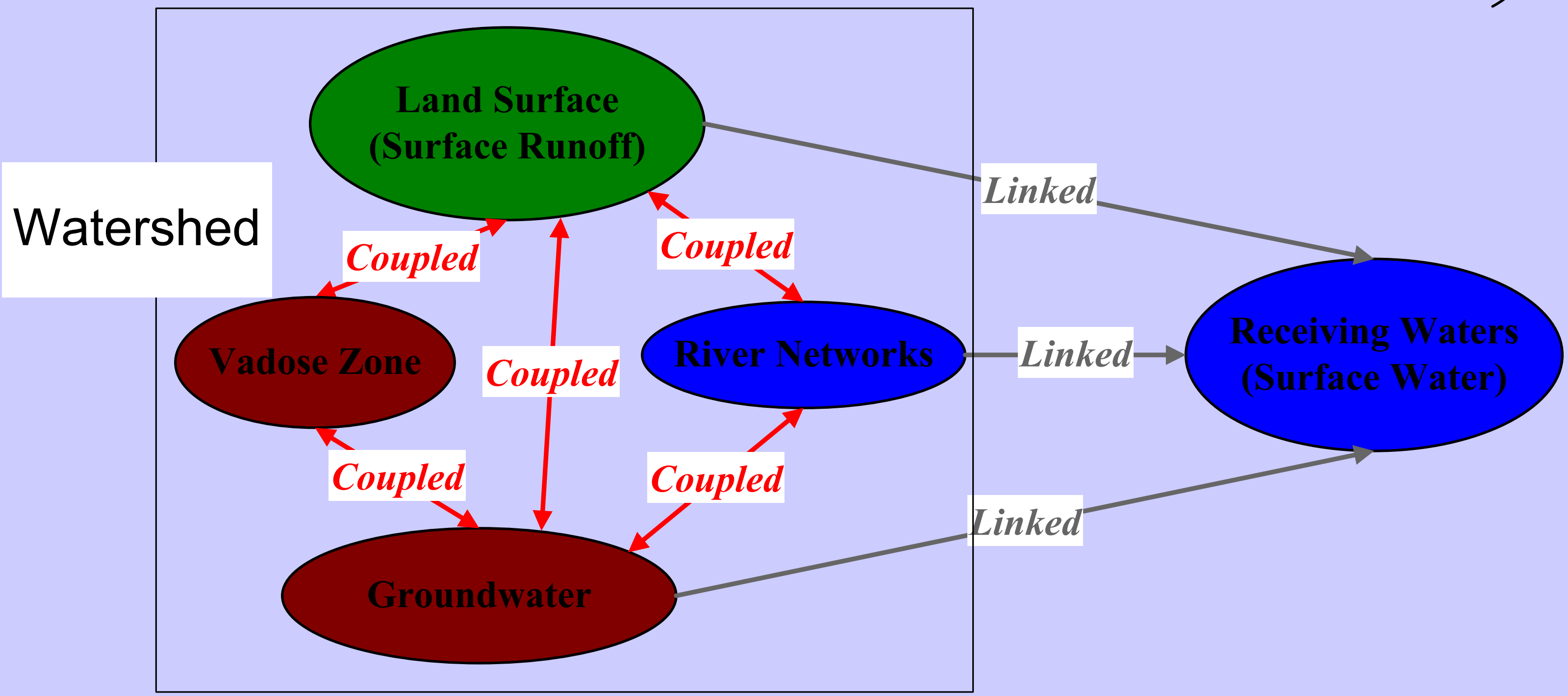

Precipitation
Snow
Precipitation Excess
Infiltration
Interception
Overland flow
Evapotranspiration
Recharge
Groundwater Flow
Surface runoff
Groundwater Runoff


River Network
Flow direction
Lakes/ Reservoirs
Bay/ Estuaries


Watershed
Land Surface (Surface Runoff)
Vadose Zone
River Networks
Groundwater
Receiving Waters (Surface Water)
Coupled
Coupled
Coupled
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Linked
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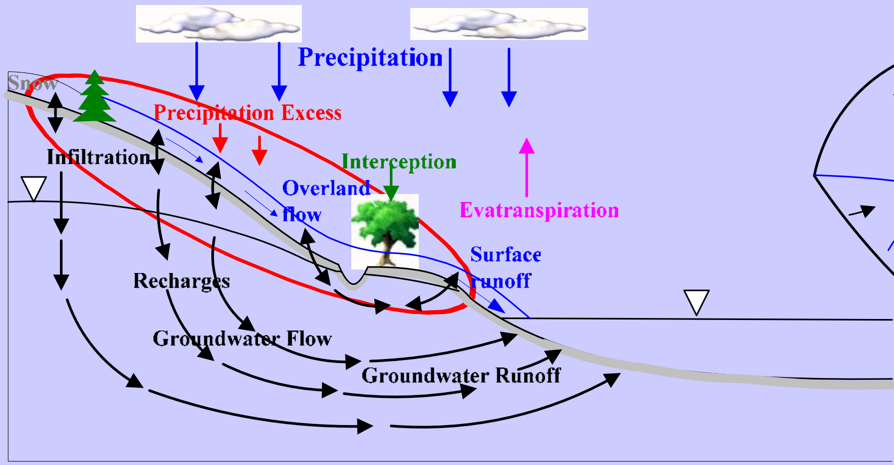
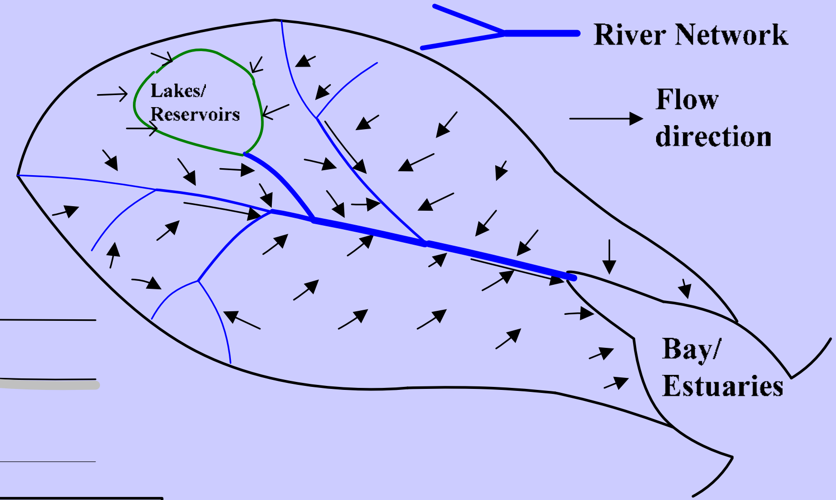
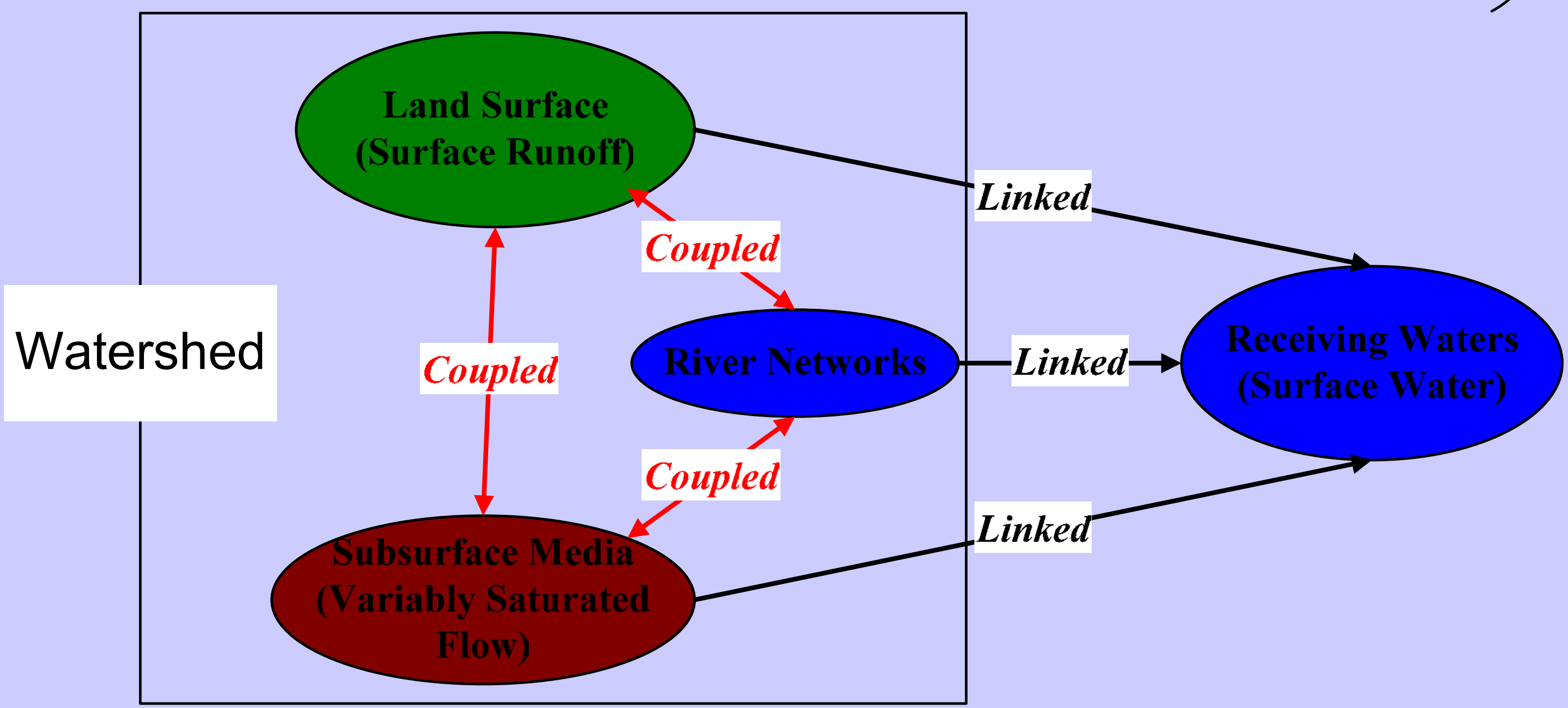


Precipitation
Snow
Precipitation Excess
Infiltration
Interception
Overland flow
Evatranspiration
Surface runoff
Recharges
Groundwater Flow
Groundwater Runoff



River Network
Flow direction
Lakes/ Reservoirs
Bay/ Estuaries



Watershed
Land Surface (Surface Runoff)
River Networks
Subsurface Media (Variably Saturated Flow)
Receiving Waters (Surface Water)
Coupled
Coupled
Coupled
Linked
Linked
Linked

Introduction to WASH123D

- Multimedia
  - Dentric Streams/Rivers/Canal/Open Channel,
  - Overland Regime,
  - Subsurface Media, and
  - Shallow Lakes/Reservoirs
- Management
  - Operational rules
- Controls
  - Weirs, gates, culverts, pumps, levees, and storage ponds
- Processes:
  - Fluid Flow, Salinity Transport, Thermal Transport, Sediment Transport, and Water Quality Transport

Theoretical Basis of WASH123D

(1) Governing Equations and particular features

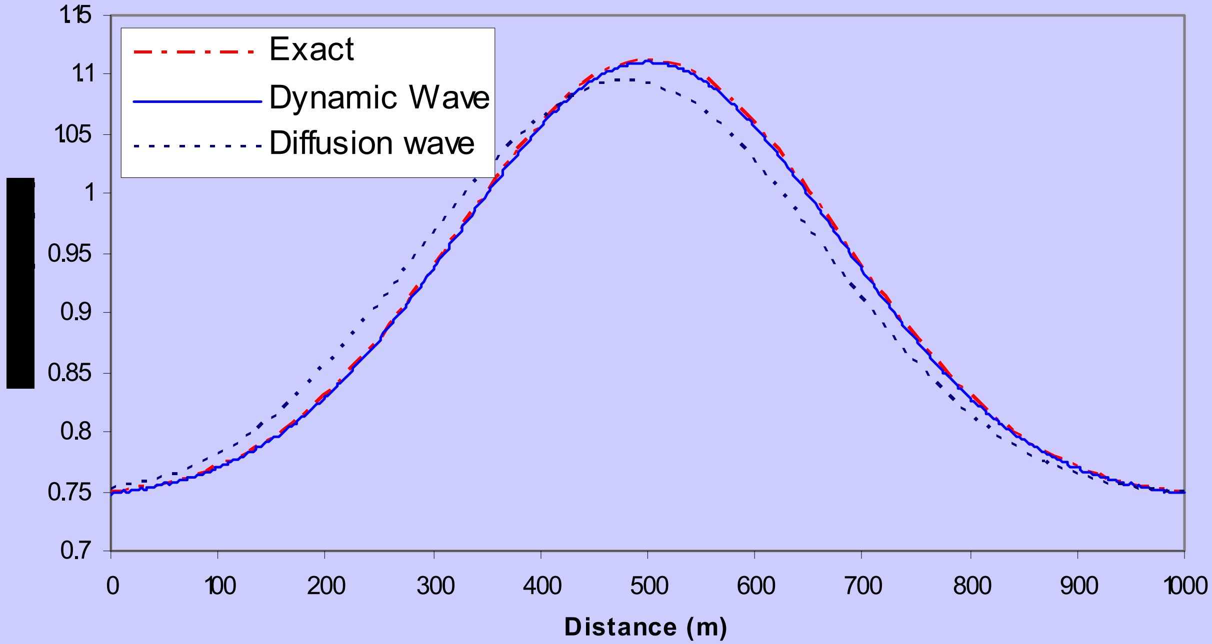
- **Fluid Flows**
  - 1D St Venant Equations for River Networks: kinematic, diffusive, and fully dynamic (MOC) waves
  - 2D St Venant Equations for Overland Regime: kinematic, diffusive, and fully dynamic (MOC) waves, as well as Lumped Models such as SCS
  - 3D Richard Equation for Subsurface Media (both Vadose and Saturated Zones): Saturated-unsaturated conditions
- **Salinity, Thermal, and Sediment Transport**
  - Modified Advection-Dispersion Equations with phenomenological approaches for erosion and deposition
- **Water Quality Transport**
  - Advection-Dispersion-Reaction Equations with reaction-based mechanistic approaches to water quality modeling - a new paradigm

The Need of Fully Various Wave Options in River Flow

- This example involves one-dimensional flow problems with three cases to illustrate the capability of the model and the need of including optional dynamic and diffusive waves to simulate
  - (a) subcritical,
  - (b) mixed subcritical and supercritical, and
  - (c) hydraulic jump problems
- The problem was described in MacDonald et al.
- The total length of the channel is 1,000 m.
- A constant flow of 20 m^3/s passes through the upstream boundary. The downstream boundary condition depends on flow configuration and the approach taken in modeling hydraulics in channels.

(a) Subcritical problem

- The channel is rectangular with a width of 10 m. outlet. The Manning's n is 0.03. The bed slope is given by an analytical function of the water depth. A water depth of 0.748409 m is specified at the downstream.

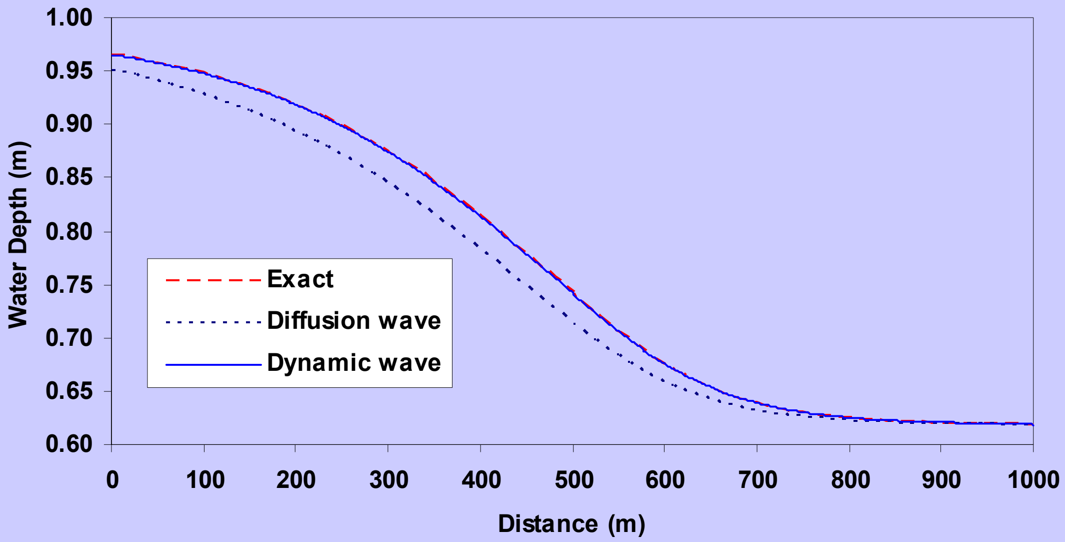


- It is seen that the FDW approach yields excellently accurate results while the DIW approach produces some errors.

(b) Mixed subcritical and supercritical problem

- The channel is rectangular with a width of 10 m. The Manning's n value is 0.02. The bottom slope is variable such that the flow condition at the inflow is subcritical and is supercritical at the outlet.

- For the dynamic wave approach, only one inflow boundary condition is needed. For diffusive wave model, two boundary conditions are needed.

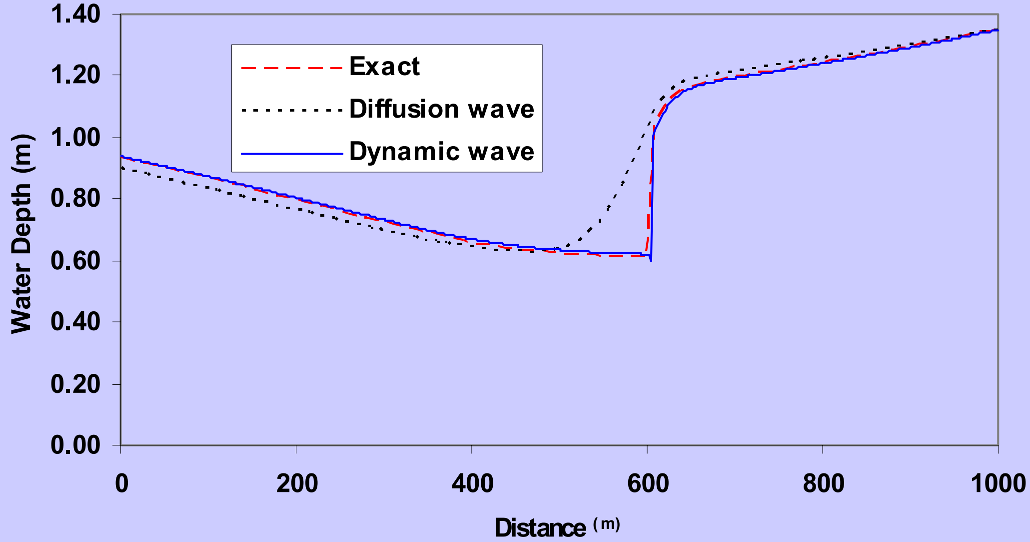


- The dynamic wave model yields good accurate simulations. The diffusive wave model also provides satisfactory results (4% error in water depth).
- It is interesting to note that the DIW model requires more input data than the FDW model, yet yields poorer simulations.

(c) Hydraulic jump problems

- The channel is trapezoidal. The side slope of the trapezoidal cross-section is 1:1. The Manning's n is 0.02. There is an abrupt change in the bed slope at x = 500 m, causing a hydraulic jump. The bottom elevation and bed slope were given in MacDonald et al.

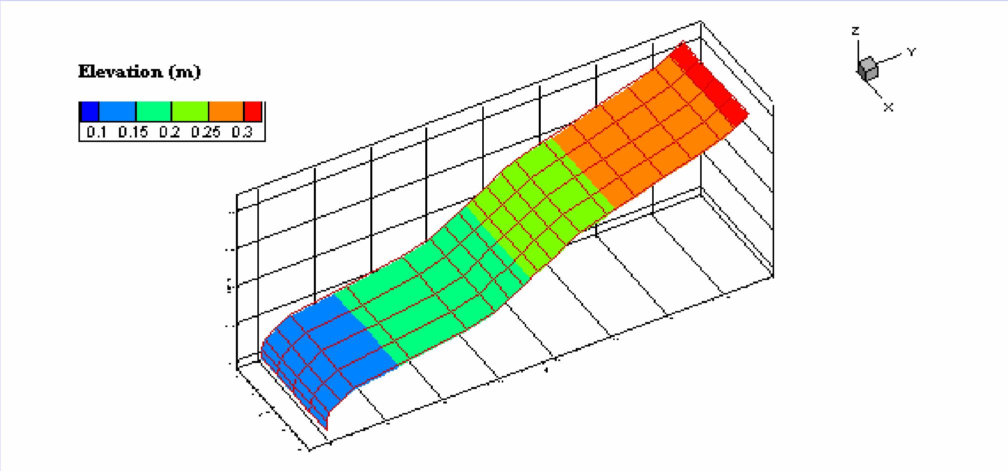
- Both inflow and outflow boundaries are subcritical. At the downstream outlet, a specified water depth of 1.349963 m is applied. This is a non-trivial problem with source terms (roughness and bed slope).



- As expected, the accuracy of the diffusive wave approximation for this mixed flow case is not satisfactory. The error induced by diffusive wave approximation is high at the supercritical zone.

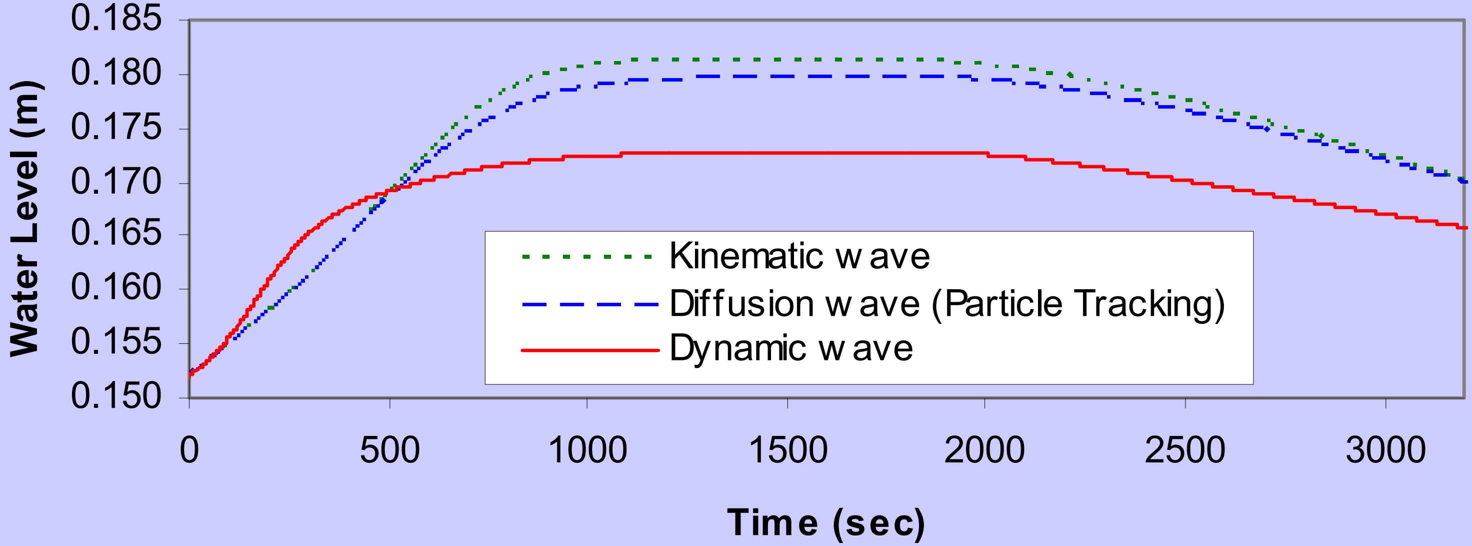
The Need of Fully Various Wave Options in Overland Flow

- This example is a two-dimensional overland flow problem. A rainfall-runoff process on an impervious curved surface is simulated. A Manning's n of 0.02 is used. The average bottom slope is 0.00133. The rainfall intensity is 3.0^{-5} m/s for 1,800 seconds (30 minutes).
- A specified water depth of 0.1 m is applied to the downstream end boundary. All other sides are assumed to be no-flow boundaries.



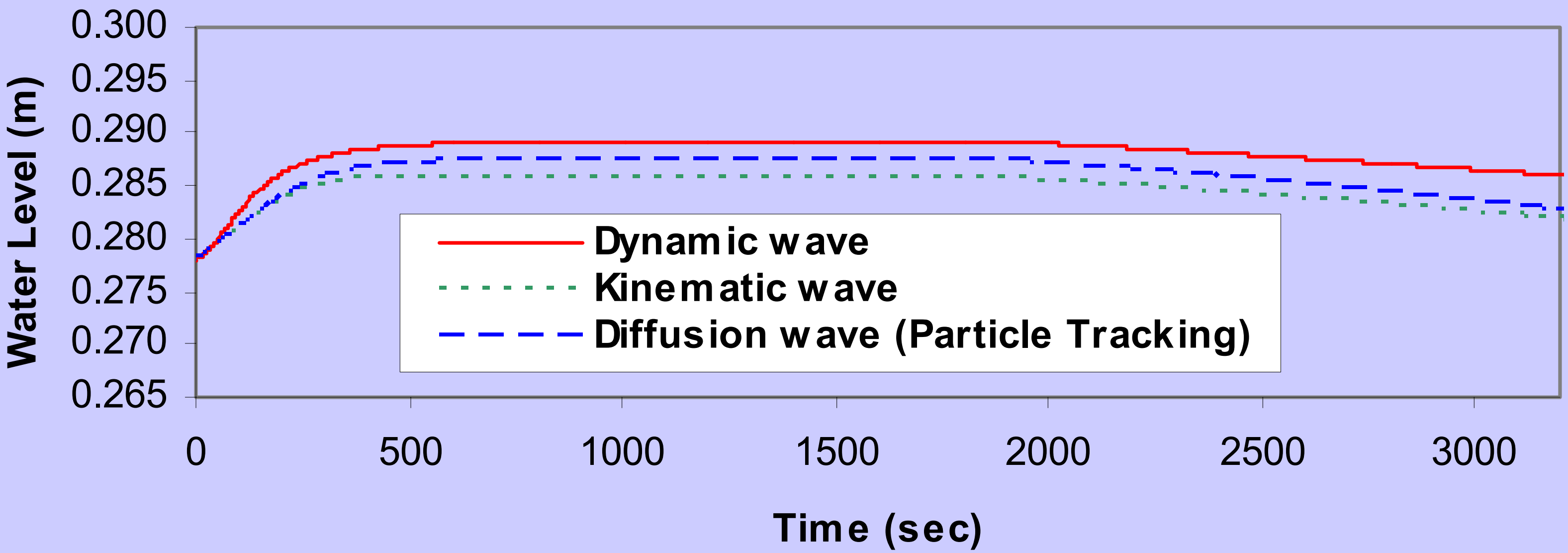
- **The purpose of this numerical experiment is to compare the simulation results obtained with different computational methods for 2-D overland flow and validate the numerical implementation for dynamic, diffusive and kinematic wave models.**

- The computed water levels at a node close to the downstream end were compared.



- The maximum value of water level, found to be 0.173 m, 0.180 m and 0.181 m, was obtained with fully dynamic wave (MOC), diffusive wave (SL), and kinematic wave (SL) approaches.
- The difference between the dynamic wave and diffusive wave models is about 6%. This may indicate the diffusive wave approximation is not accurate for this problem.

- The computed water levels at a node close to the upstream end were compared.



- The maximum water depth at this site is 0.01124 m, 0.0094 m and 0.00776 m for FDW (MOC), DIW (SL), and KIW (SL), respectively.
- The differences between the fully dynamic wave and diffusive/kinematic wave models at the upstream nodes are smaller than those at the downstream nodes as expected.

(2) Boundary Conditions and particular features

- **Global Boundaries**
  - Flows
    - For subsurface flow, specify pressure head, flux, pressure gradient, or variable
    - For surface flow, specify water depth, flow rate, or rating curve.
  - Salinity, Sediment, and Reactive chemical Transport
    - Specify concentration, flux, concentration gradient or variable.
  - Thermal Transport
    - Specify temperature, heat flux, temperature gradient or variable, and heat budget at the air-media interface.

- **Internal Source and Internal Boundary Conditions**
  - Pumps and Operational Rules
  - Junctions - explicitly enforced mass balance
  - Control Structures - weirs, gates, culverts, and levees.

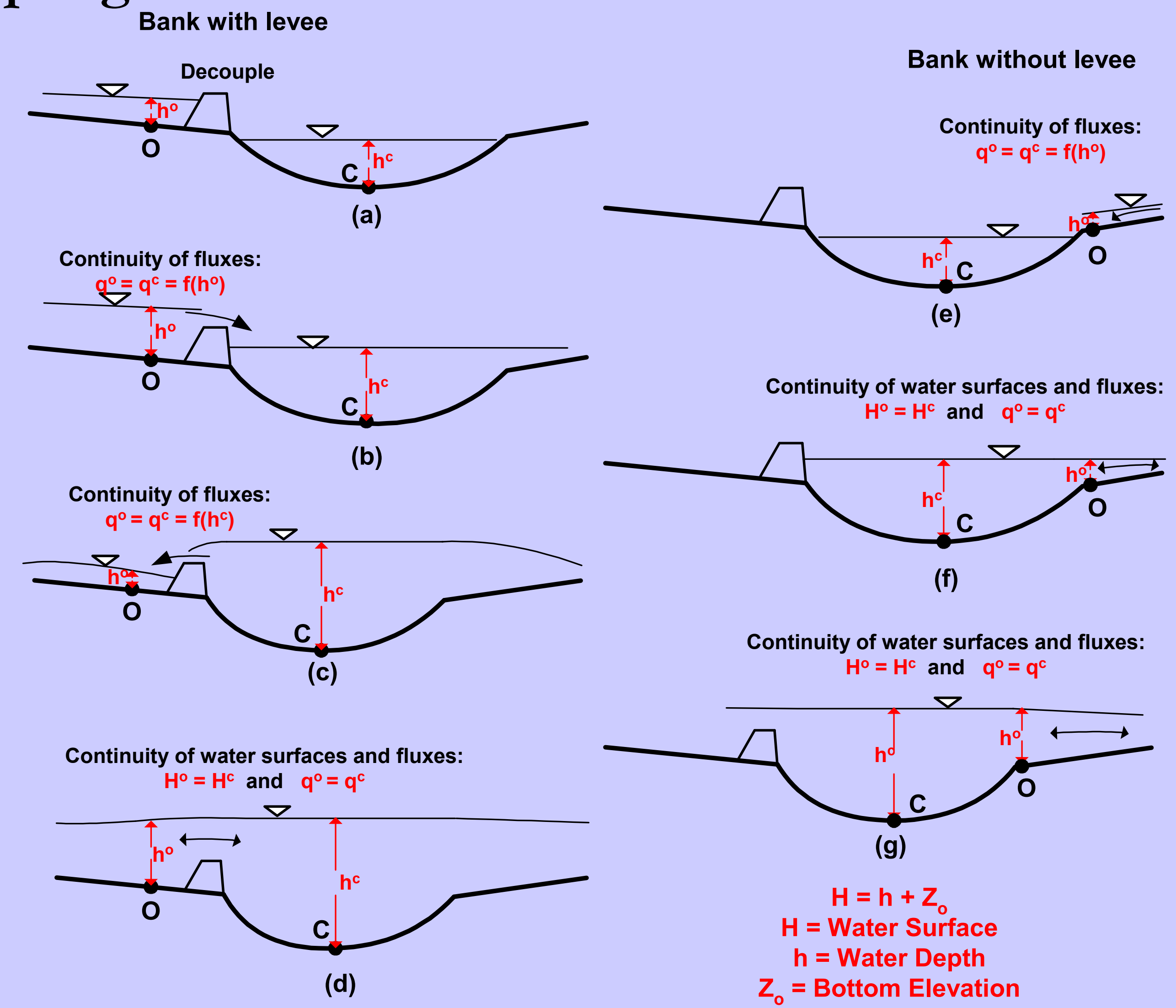
- **Media Interfaces**
  - Continuity of Fluxes Across Media Interfaces
  - Continuity of State Variables Across Media Interfaces or
  - Linkage Terms for Special Cases.

(3) Numerical Methods and particular features

- **Discretization**
  - Flows
    - For subsurface flow: Use Galerkin Finite Element Methods (FEM)
    - For surface flow: Use Particle Tracking Methods for the kinematic wave approaches; Use Finite Element Methods or Particle Tracking Methods for the diffusive wave approaches; Use Lagrangian-Eluerian Finite Element Methods for the fully dynamic wave approaches.
  - Salinity, Thermal, Sediment, and Reaction-Based Water Quality Transport
    - Use Finite Element Methods or Particle Tracking Methods
- **Solvers**
  - Direct Band Matrix; Basic Point Iterations Methods; Basic Line Iterations; Preconditioned Preconditioned Conjugate Gradient Methods with Point Iterations, Incomplete Cholesky Decomposition, and Line Iterations as Preconditioners; Algebraic Multigrid Methods
- **Planned Features**
  - Optimal discretization for advection term with adaptive local grid refinement, peak capturing, and Lagrangian-Eulerian decoupling (LEZOOMPC).

Rigorous Coupling Among Media

1D/2D Coupling



For each rive node I, there are two overland nodes J and K interacting with the river node I (see Figure). Four additional equations are needed to govern the four additional unknowns of coupling: Q_I^{01}, Q_I^{02}, Q_J^{o}, and Q_K^{o}. These equations are obtained by imposing continuity of state variables and fluxes or flux formulation.

$$\begin{bmatrix} \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ A_{I1}^{c} & A_{I2}^{c} & \cdots & A_{II}^{c} & \cdots & \cdots & A_{IN}^{c} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \end{bmatrix} \begin{Bmatrix} H_1^c \\ H_2^c \\ \vdots \\ H_I^c \\ \vdots \\ \vdots \\ H_N^c \end{Bmatrix} = \begin{Bmatrix} R_1^c \\ R_2^c \\ \vdots \\ R_I^c \\ \vdots \\ \vdots \\ R_N^c \end{Bmatrix} + \begin{Bmatrix} Q_1^{o1} \\ Q_2^{o1} \\ \vdots \\ Q_I^{o1} \\ \vdots \\ \vdots \\ Q_N^{o1} \end{Bmatrix} + \begin{Bmatrix} Q_1^{o2} \\ Q_2^{o2} \\ \vdots \\ Q_I^{o2} \\ \vdots \\ \vdots \\ Q_N^{o2} \end{Bmatrix}$$

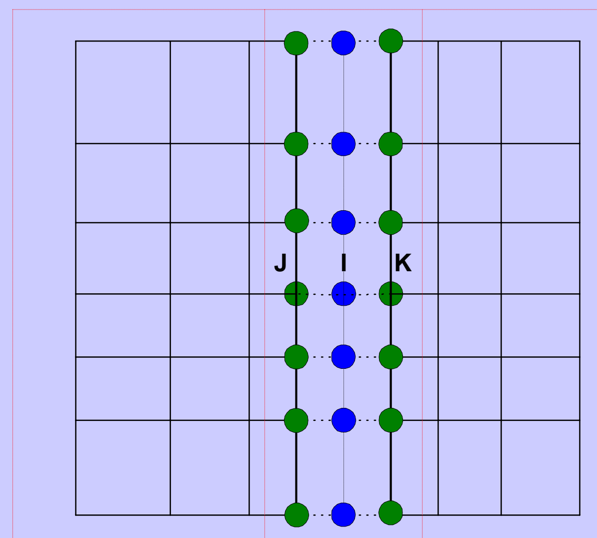
$$Q_J^o = Q_I^{o1}$$

$$H_J^o = H_I^c \quad \text{or} \quad Q_I^{o1} = f_1(h_J^o, h_I^c)$$

$$Q_K^o = Q_I^{o2}$$

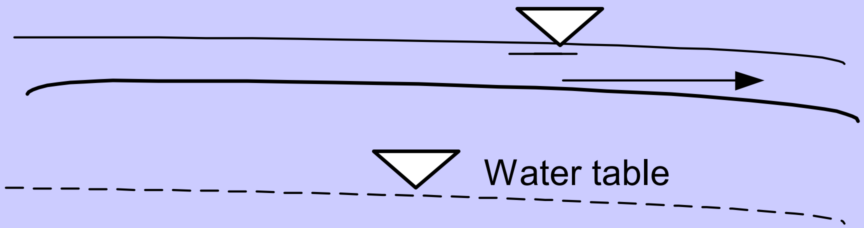
$$H_K^o = H_I^c \quad \text{or} \quad Q_I^{o2} = f_2(h_J^o, h_I^c)$$

$$\begin{bmatrix} A_{11}^{o} & A_{12}^{o} & \cdots & \cdots & \cdots & \cdots & A_{1M}^{o} \\ A_{21}^{o} & \cdots & \cdots & \cdots & \cdots & \cdots & A_{2M}^{o} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ A_{J1}^{o} & A_{J2}^{o} & \cdots & A_{JJ}^{o} & \cdots & \cdots & A_{JM}^{o} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ A_{K1}^{o} & A_{K2}^{o} & \cdots & \cdots & A_{KK}^{o} & \cdots & A_{KM}^{o} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ A_{M1}^{o} & A_{M2}^{o} & \cdots & \cdots & \cdots & \cdots & A_{MM}^{o} \end{bmatrix} \begin{Bmatrix} H_1^o \\ H_2^o \\ \vdots \\ H_J^o \\ \vdots \\ H_K^o \\ \vdots \\ H_M^o \end{Bmatrix} = \begin{Bmatrix} R_1^o \\ R_2^o \\ \vdots \\ R_J^o \\ \vdots \\ R_K^o \\ \vdots \\ R_M^o \end{Bmatrix} + \begin{Bmatrix} \vdots \\ \vdots \\ \vdots \\ Q_J^o \\ \vdots \\ Q_K^o \\ \vdots \\ \vdots \end{Bmatrix}$$



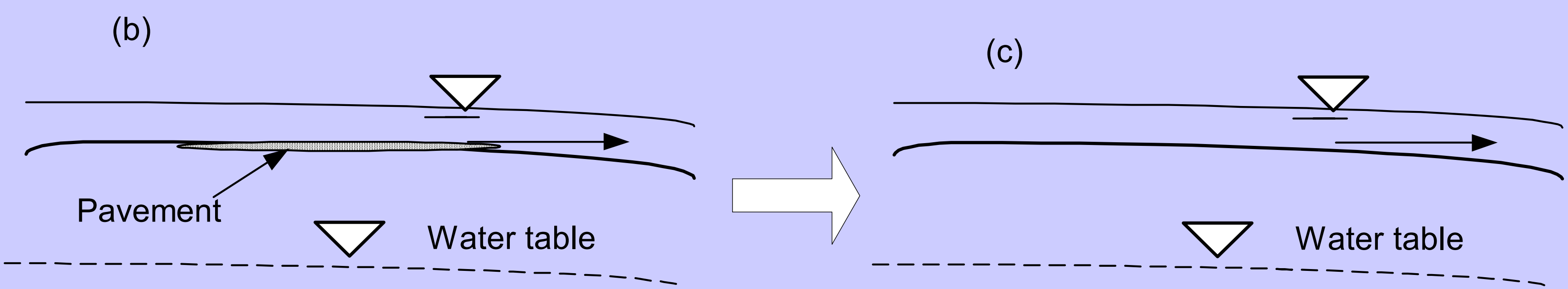
2D/3D Coupling

(a)



The interface flux Q is determined by

$h^o = h^s$ and $Q^o = Q^s$ on the interface



The interfaceflux Q is determined by

$Q=K(h^o-h^s)$ on the interface

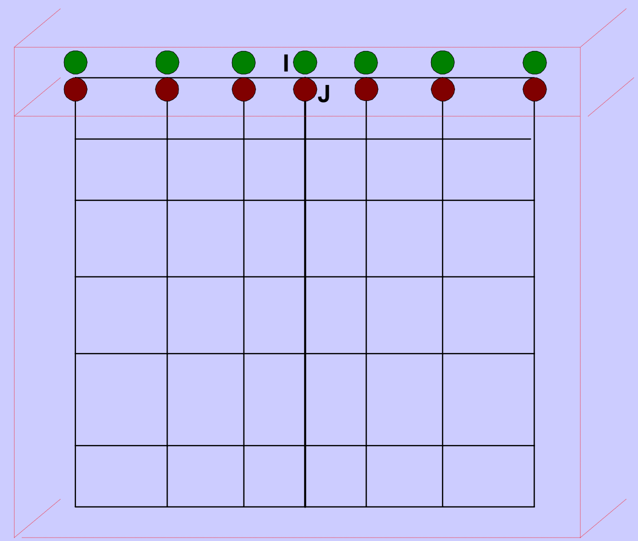
For each rive node I, there is one subsurface node J interacting with the overland node I (see Figure). Two additional equations are needed to govern the two additional unknowns of coupling: Q_I^{io} and Q_J^{s}. These equations are obtained by imposing continuity of state variables and fluxes or flux formulation.

$$\begin{bmatrix} \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ A_{I1}^{o} & A_{I2}^{o} & \cdots & A_{II}^{o} & \cdots & \cdots & A_{IN}^{o} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \end{bmatrix} \begin{Bmatrix} H_1^{o} \\ H_2^{o} \\ \vdots \\ H_I^{o} \\ \vdots \\ \vdots \\ H_N^{o} \end{Bmatrix} = \begin{Bmatrix} R_1^{o} \\ R_2^{o} \\ \vdots \\ R_I^{o} \\ \vdots \\ \vdots \\ R_N^{o} \end{Bmatrix} + \begin{Bmatrix} Q_1^{io} \\ Q_2^{io} \\ \vdots \\ Q_I^{io} \\ \vdots \\ \vdots \\ Q_N^{io} \end{Bmatrix}$$

$$Q_J^{s} = Q_I^{io}$$

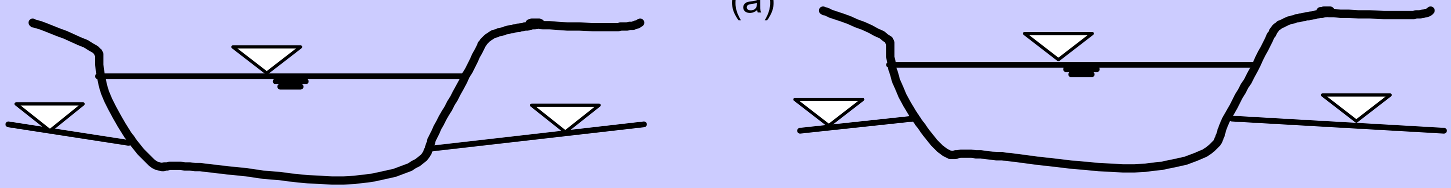
$$H_J^{s} = H_I^{o} \quad \text{or} \quad Q_I^{io} = K(H_I^{o} - H_J^{s})$$

$$\begin{bmatrix} A_{11}^{s} & A_{12}^{s} & \cdots & \cdots & \cdots & \cdots & A_{1M}^{s} \\ A_{21}^{s} & \cdots & \cdots & \cdots & \cdots & \cdots & A_{2M}^{s} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ A_{J1}^{s} & A_{J2}^{s} & \cdots & A_{JJ}^{s} & \cdots & \cdots & A_{IM}^{s} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ A_{M1}^{o} & A_{M2}^{o} & \cdots & \cdots & \cdots & \cdots & A_{MM}^{o} \end{bmatrix} \begin{Bmatrix} H_1^{s} \\ H_2^{s} \\ \vdots \\ H_J^{s} \\ \vdots \\ \vdots \\ H_M^{s} \end{Bmatrix} = \begin{Bmatrix} R_1^{s} \\ R_2^{s} \\ \vdots \\ R_J^{s} \\ \vdots \\ \vdots \\ R_M^{o} \end{Bmatrix} + \begin{Bmatrix} \vdots \\ \vdots \\ \vdots \\ Q_J^{s} \\ \vdots \\ \vdots \\ \vdots \end{Bmatrix}$$



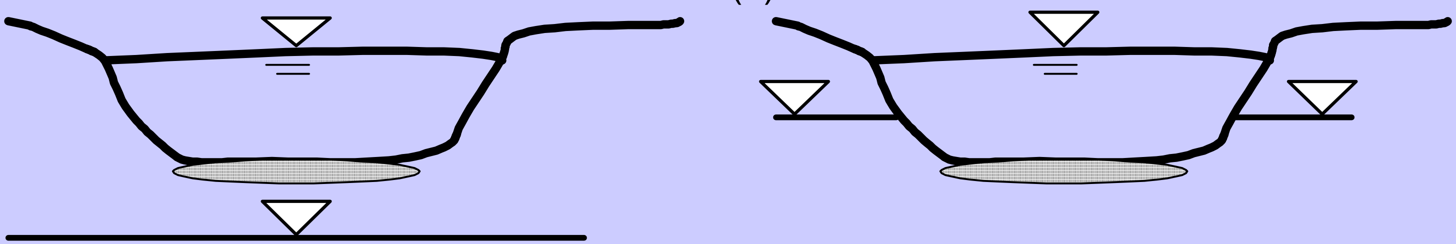
3D/1D Coupling

(a)

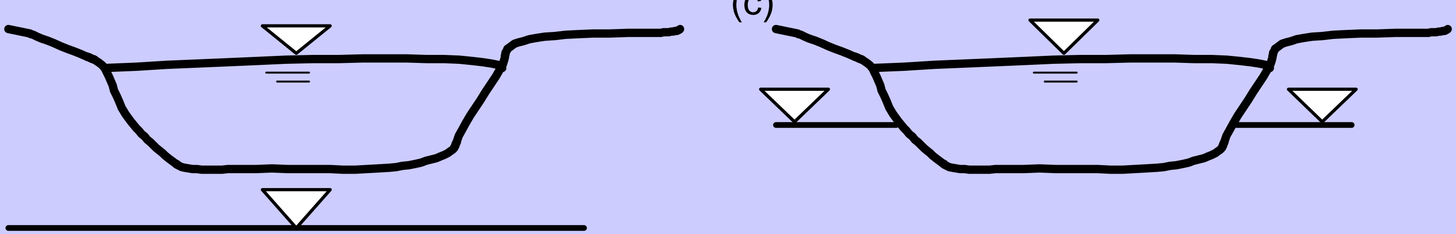


The interface flux Q is determined by $h^c = h^s$ and $Q^c = Q^s$ on the interface

(b)

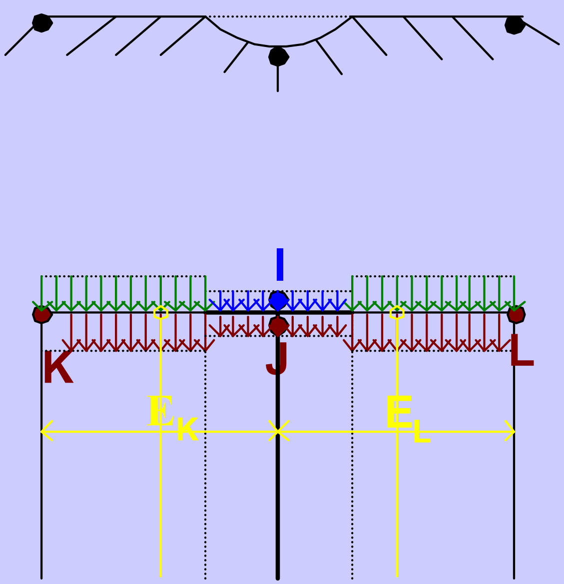


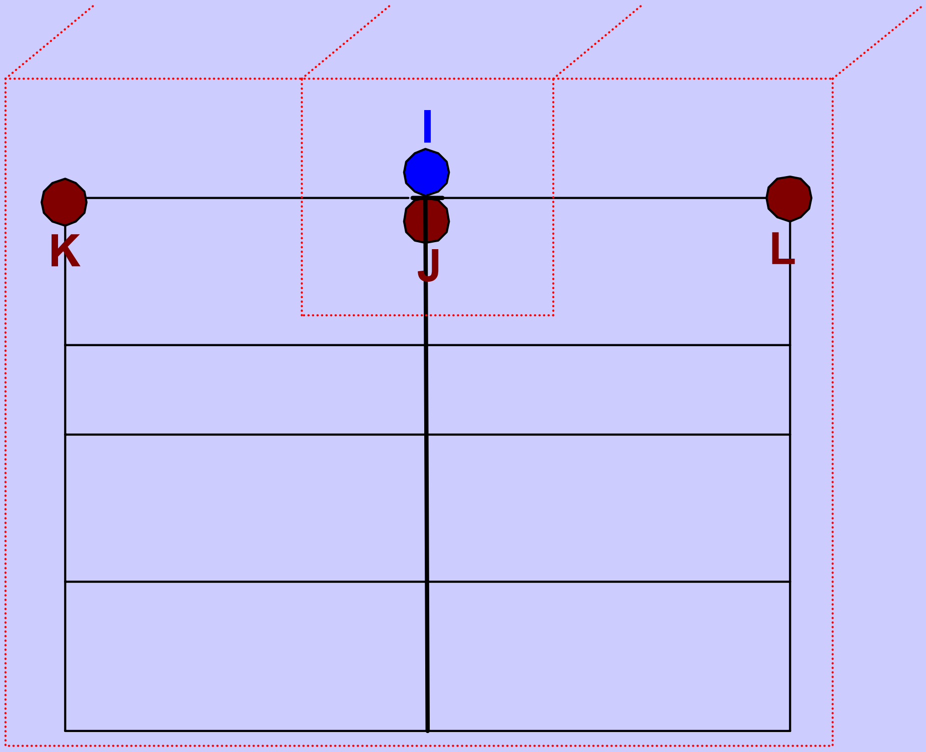
(c)



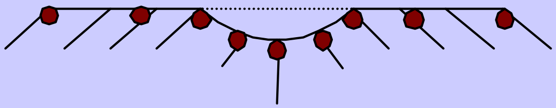
The interfaceflux Q is determined by $Q=K(h^c-h^s)$ on the interface

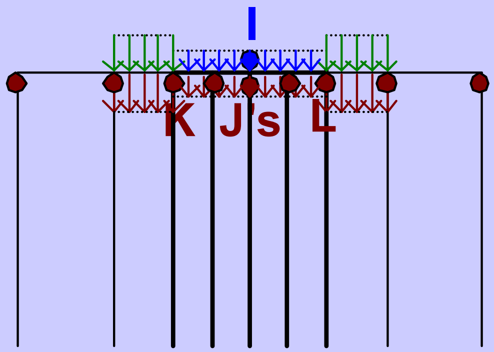
Case A: River-subsurface interface is conceptualized as lines on the grid, river has zero-width and zero-depth

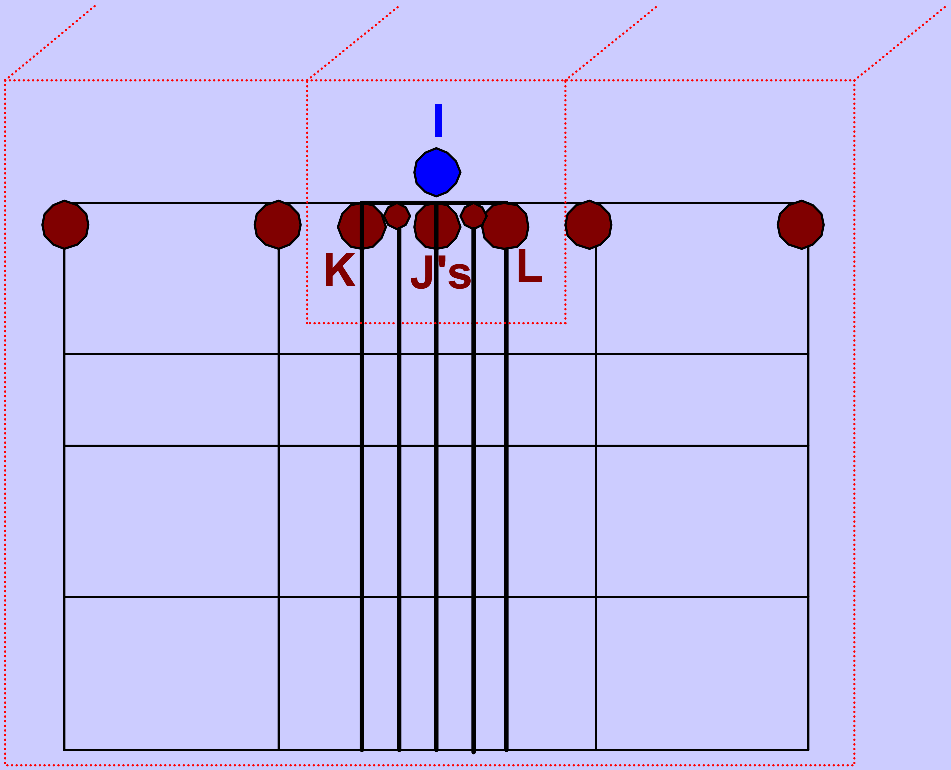




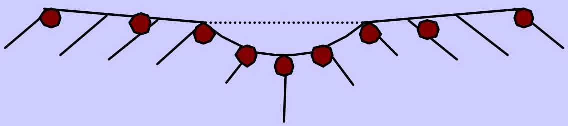
Case B: Subsurface-river interface is conceptualized as planes on the grid, river has finite-width and zero-depth

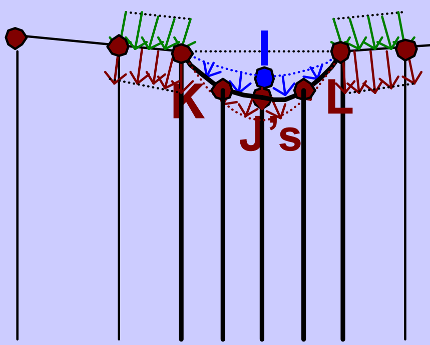


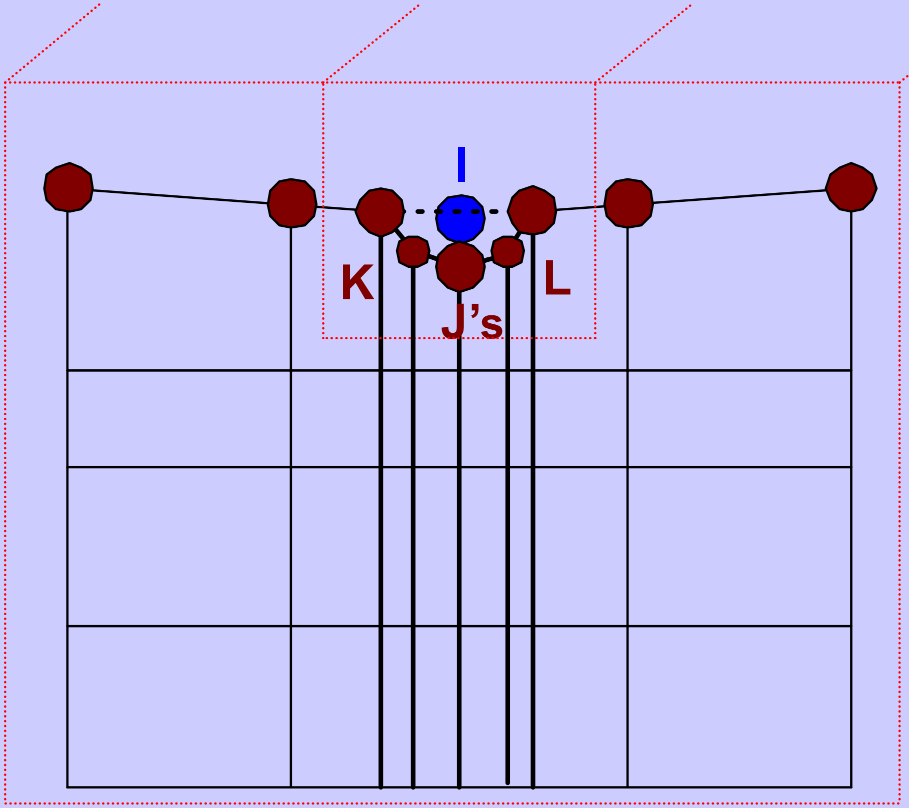




Case C: Subsurface-river interface is conceptualized as surfaces on the grid, river has finite-width and finite-depth







Case A: For each rive node I, there are three subsurface nodes K, J, and L interacting with the river node I (see Figure). Four additional equations are needed to govern the four additional unknowns of coupling: Q_I^{ic}, Q_K^{s}, Q_J^{s}, and Q_L^{s}. These equations are obtained by imposing continuity of state variables and fluxes or flux formulation.

$$
\begin{bmatrix}
\cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\
\cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\
\cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\
A_{I1}^c & A_{I2}^c & \cdots & A_{II}^c & \cdots & \cdots & A_{IN}^c \\
\cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\
\cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\
\cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots
\end{bmatrix}
\begin{Bmatrix} H_1^c \\ H_2^c \\ \cdots \\ H_I^c \\ \cdots \\ \cdots \\ H_N^c \end{Bmatrix}
=
\begin{Bmatrix} R_1^c \\ R_2^c \\ \cdots \\ R_I^c \\ \cdots \\ \cdots \\ R_N^c \end{Bmatrix}
+
\begin{Bmatrix} Q_1^{ic} \\ Q_2^{ic} \\ \cdots \\ Q_I^{ic} \\ \cdots \\ \cdots \\ Q_N^{ic} \end{Bmatrix}
$$

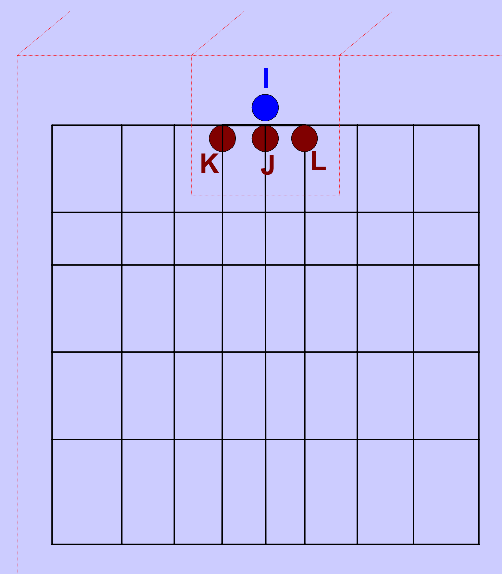
$$Q_I^{ic} + Q_K^{rain} + Q_L^{rain} = Q_K^{s} + Q_J^{s} + Q_L^{s}$$

$$H_I^c = H_J^s \quad \text{or} \quad Q_I^{ic} = K(H_I^c - H_J^s)$$

$$H_K^s = H_K^{ponding} \quad \text{or} \quad Q_K^s = Q_K^{rain} + \frac{1}{4} Q_I^{ic}$$

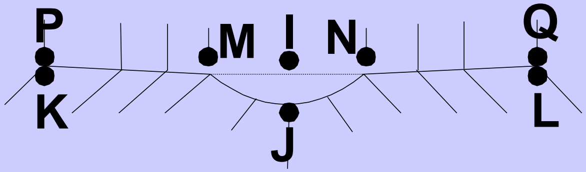
$$H_L^s = H_L^{ponding} \quad \text{or} \quad Q_L^s = Q_L^{rain} + \frac{1}{4} Q_I^{ic}$$

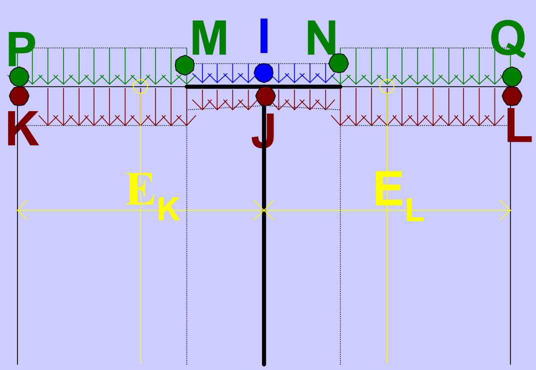
$$
\begin{bmatrix}
A_{11}^s & A_{12}^s & \cdots & \cdots & \cdots & \cdots & A_{1M}^s \\
A_{21}^s & \cdots & \cdots & \cdots & \cdots & \cdots & A_{2M}^s \\
\cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\
A_{K1}^s & A_{K2}^s & A_{KK}^s & \cdots & \cdots & \cdots & A_{KM}^s \\
A_{J1}^s & A_{J2}^s & \cdots & A_{JJ}^s & \cdots & \cdots & A_{IM}^s \\
A_{L1}^s & A_{L2}^s & A_{«}^s & \cdots & \cdots & \cdots & A_{LM}^s \\
\cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\
A_{M1}^o & A_{M2}^o & \cdots & \cdots & \cdots & \cdots & A_{MM}^o
\end{bmatrix}
\begin{Bmatrix} H_1^s \\ H_2^s \\ \cdots \\ H_K^s \\ H_J^s \\ H_L^s \\ \cdots \\ H_M^s \end{Bmatrix}
=
\begin{Bmatrix} R_1^s \\ R_2^s \\ \cdots \\ R_K^s \\ R_J^s \\ R_L^s \\ \cdots \\ R_M^o \end{Bmatrix}
+
\begin{Bmatrix} \cdots \\ \cdots \\ \cdots \\ Q_K^s \\ Q_J^s \\ Q_L^s \\ \cdots \\ \cdots \end{Bmatrix}
$$

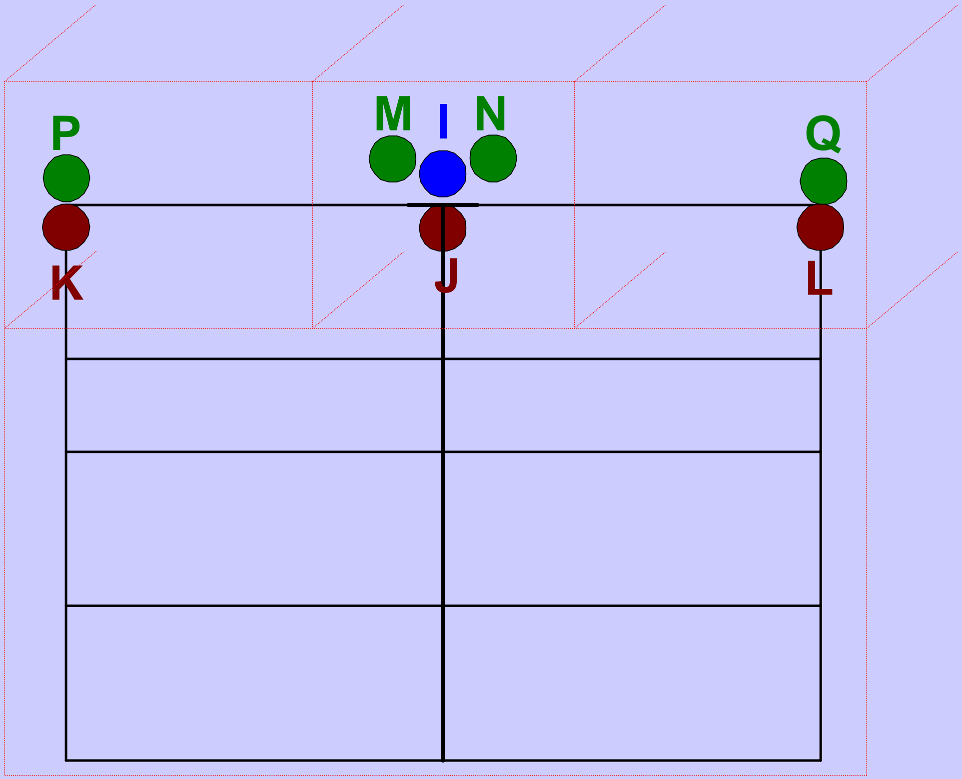


3D/2D/1D Coupling

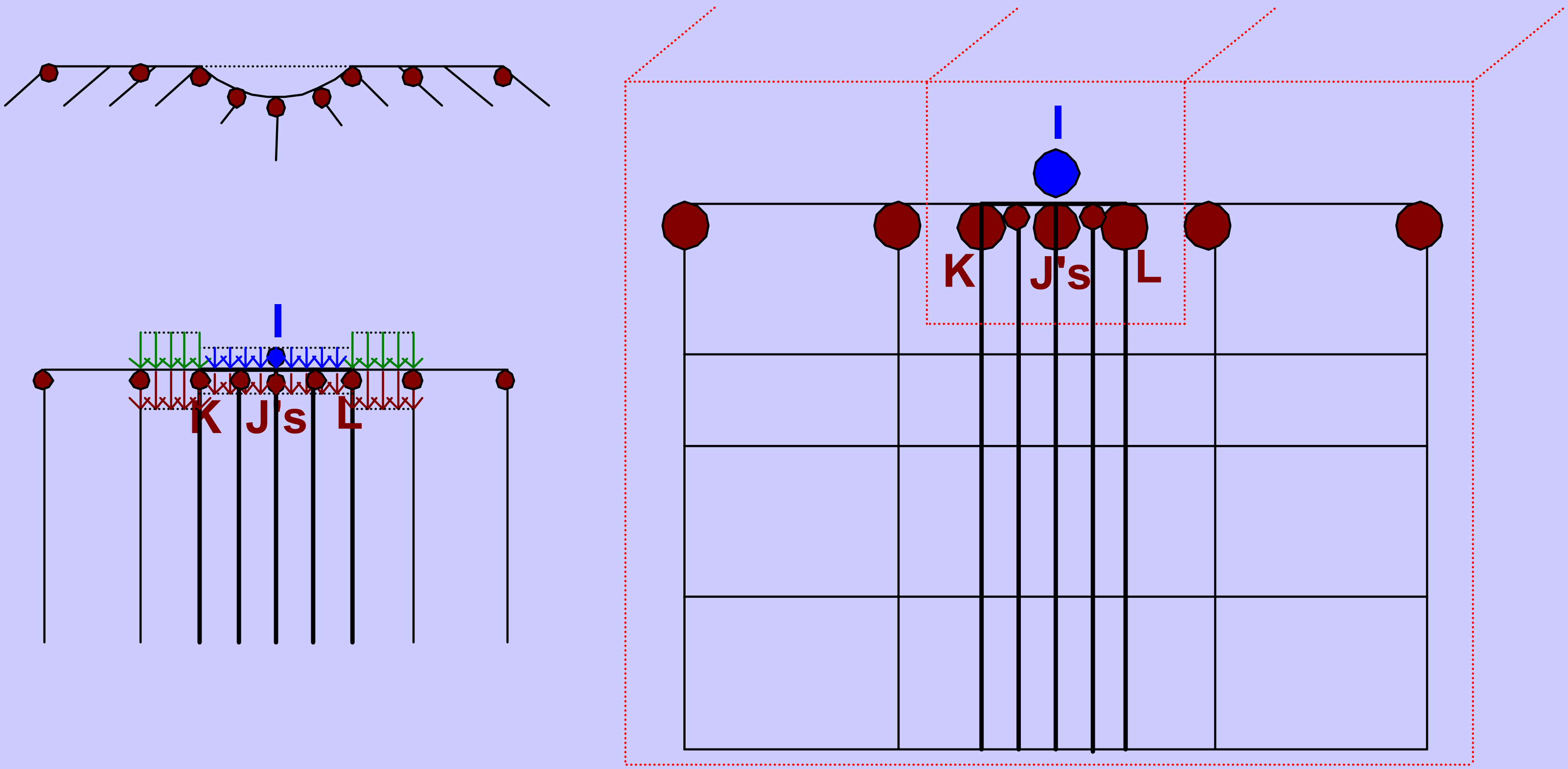
Case A: River-subsurface interface is conceptualized as lines on the grid, river has zero-width and zero-depth



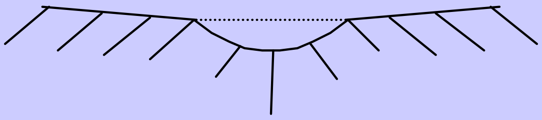


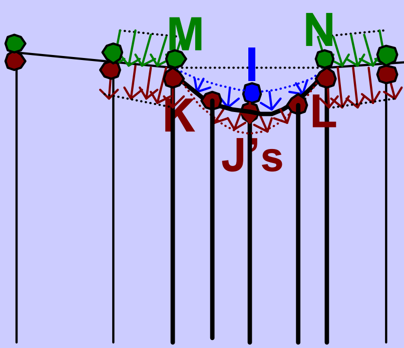


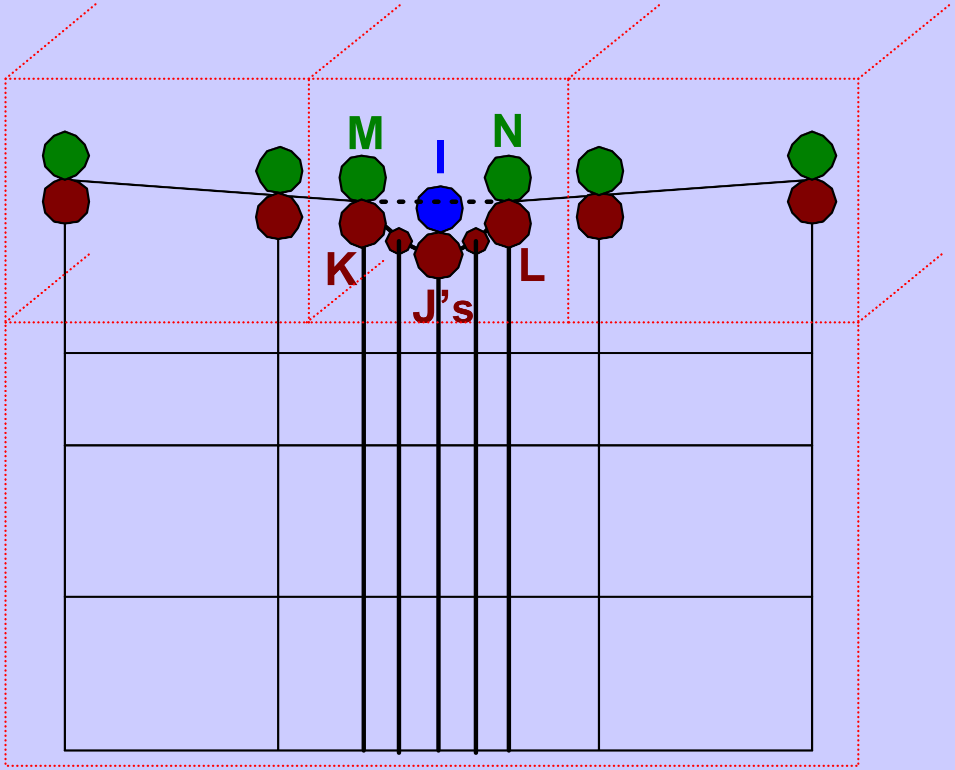
Case B: Subsurface-river interface is conceptualized as planes on the grid, river has finite-width and zero-depth



Case C: Subsurface-river interface is conceptualized as surfaces on the grid, river has finite-width and finite-depth

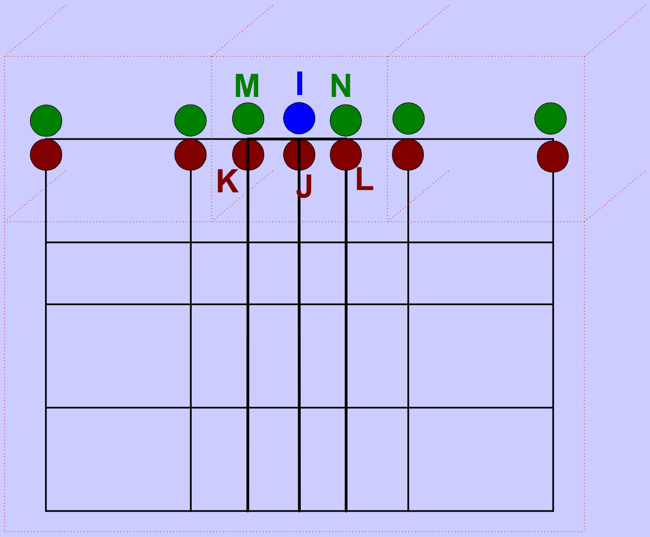




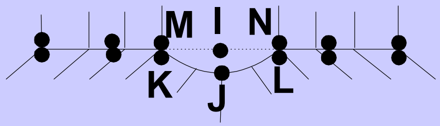


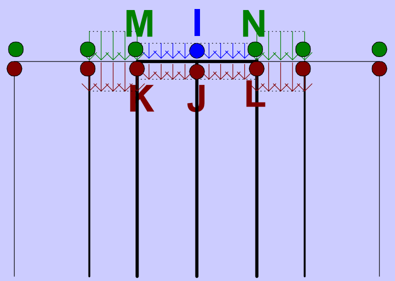
Case A: For each rive node I, there are three subsurface nodes K, J, and L and two overland nodes M and N, which interact with each other I (see Figure). There are ten additional unknowns on top of the six unknowns H_I^c, H_M^o, H_N^o, H_K^s, H_J^s, and H_L^s. These ten additional equations are listed below. Thus ten additional equations are needed to govern these ten additional unknowns of coupling. These equations are obtained by imposing continuity of state variables and fluxes or flux formulation as shown in the next slide.

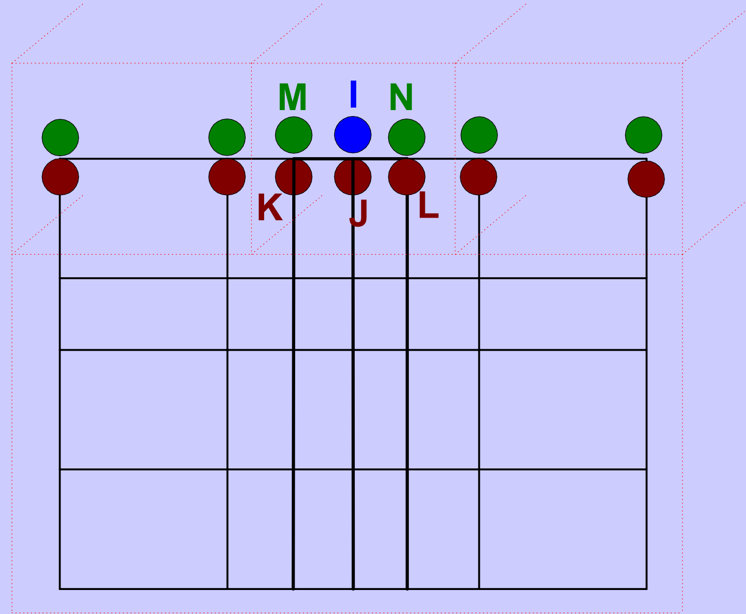
- The equation for the canal node I: Q_I^{o1}, Q_I^{o2}, Q_I^{ic}
- The equation for the overland node K: Q_M^o, Q_M^{io}
- The equation for the overland node L: Q_N^o, Q_N^{io}
- The equation for the subsurface node K: Q_K^s
- The equation for the subsurface node J: Q_J^s
- The equation for the subsurface node L: Q_L^s



Case A: Derivation of 10 additional unknowns based on the continuity of pressure head or flux formulations







$$Q_M^o = Q_I^{o1}$$

$$H_M^o = H_I^c \quad \text{or} \quad Q_I^{o1} = f_1(H_M^o, H_I^c)$$

$$Q_N^o = Q_I^{o2}$$

$$H_N^o = H_I^c \quad \text{or} \quad Q_I^{o2} = f_2(H_N^o, H_I^c)$$

$$Q_K^s = Q_M^{io} + \frac{1}{4} Q_I^{ic}$$

$$H_K^s = H_M^o \quad \text{or} \quad Q_K^{io} = K(H_M^o - H_K^s)$$

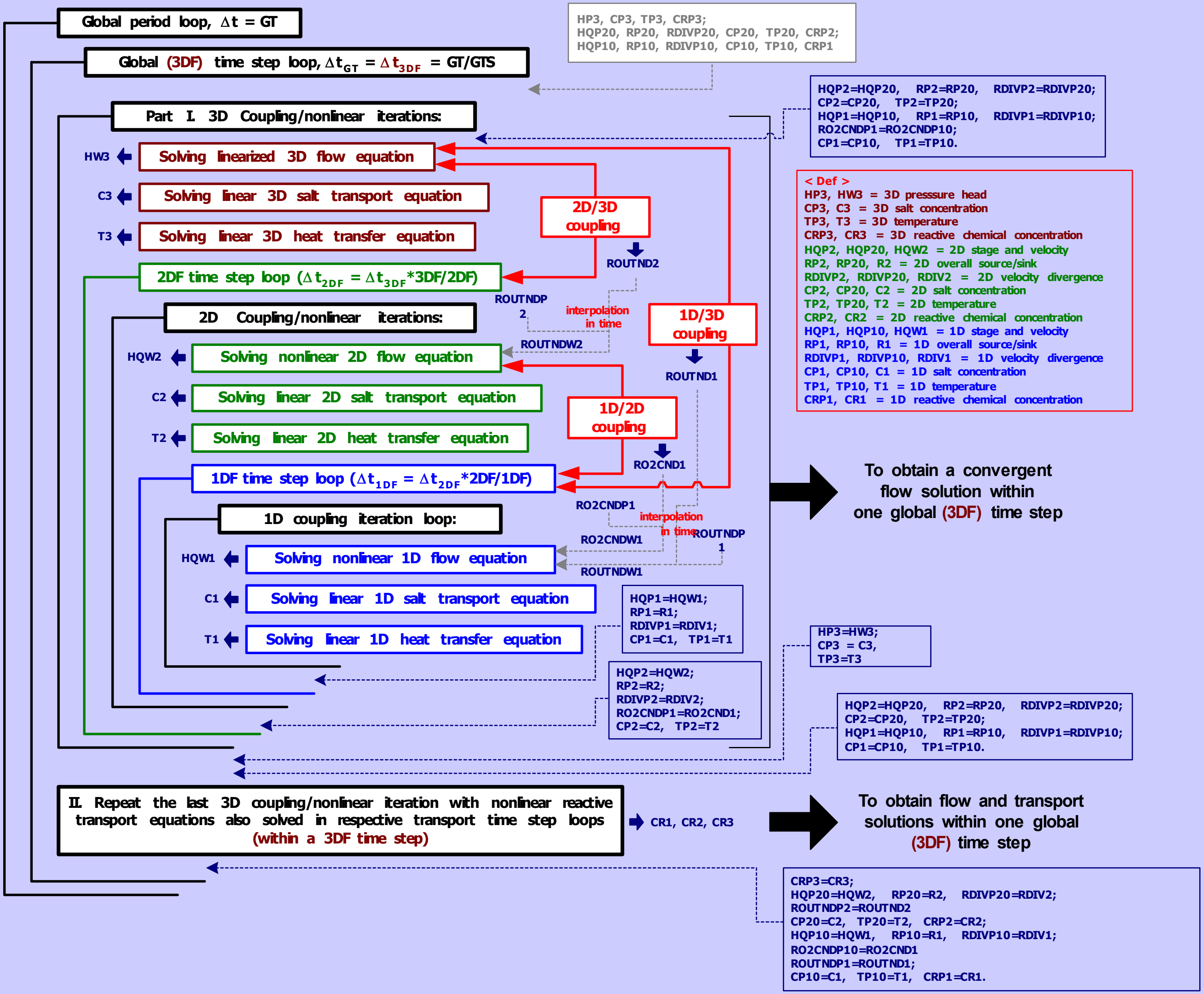
$$Q_L^s = Q_N^{io} + \frac{1}{4} Q_I^{ic}$$

$$H_L^s = H_N^o \quad \text{or} \quad Q_L^{io} = K(H_N^o - H_L^s)$$

$$Q_J^s = \frac{1}{2} Q_I^{ic}$$

$$H_J^s = H_I^c \quad \text{or} \quad Q_I^{ic} = K(H_I^c - H_J^s)$$

Vastly Different Time Scales In Mutimedia



Design Capability of WASH123D

- 1-D River/Stream Network
- 2-D Overland Regime
- 3-D Subsurface Media (both Vadose and Saturated Zones)

- Coupled 1-D River/Stream Network and 2-D Overland Regime
- Coupled 2-D Overland Regime and 3-D Subsurface
- Coupled 3-D Subsurface and 1-D River Systems

- Coupled 3-D Subsurface Media, 2-D Overland, and 1-D River Network

- Coupled 0-D Shallow Water Bodies and 1-D Canal Network

For any of the above 8 cases, one can simulate flow only, transport only, or coupled flow and transport.

Examples of WASH123D Design Capability

- Five Example Problems of Various Spatial and Temporal Scales
  - Aquifer storage
  - Overland and stream flow
  - Coupled river, overland, and subsurface flow
  - Circular dam break
  - Two-dimensional dam break
- Spatial Scales from Meters to Tens of Kilometers
- Temporal Scales from Seconds to Years

Example No. 1: Aquifer Storage Recover

Problem description

- ASR (Aquifer Storage Recovery) is to inject surface water into an aquifer and then recover for later water use.
- We aim at simulating a single ASR well.
- Some data is refer to the 1989 ASR project for Lake Okeechobee. But overall it is for demo purpose only.
- Density driven flow and transport is simulated. The injected freshwater is stored and mixed with the brackish water in the aquifer.
- The diameter of the ASR well is 24 inches.
- The screened area is located at 1300 ft to 1600 ft below land surface. So the storage zone is in the artesian aquifers. With a confining layer over it.
- The transmissivity is 4.28 x 10^6 gpd/ft.
- The effective porosity is 0.25

Conceptual Model

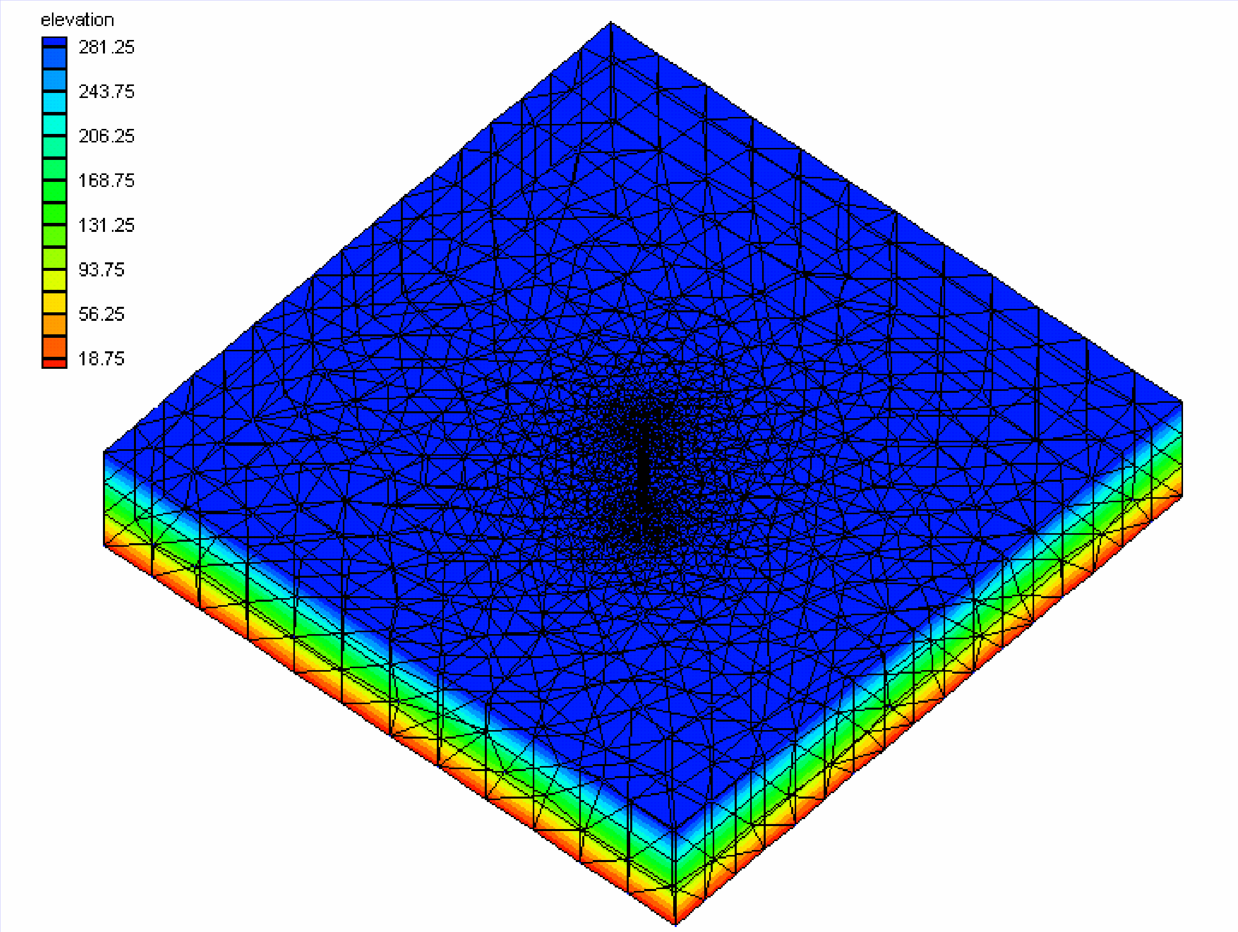
- Only the Storage zone is to be simulated.
- So this is a confined aquifer with an initial constant total head.
- The thickness of the aquifer is 300 ft.
- A rectangular area, with a scale of 1600 x 1600 ft is chosen for the modeling domain.
- The boundary is to set away from the ASR well, so that injected water is to be stored in the domain.

Model Parameters and Boundary Conditions

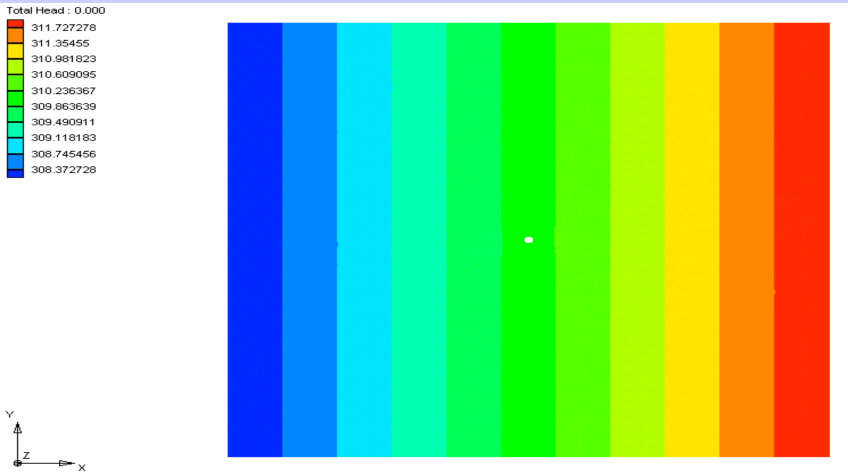
- Hydraulic conductivity: 177.6 ft/day
- Effective porosity: 0.25
- Specified head BC are assigned in the direction of natural groundwater flow;
- Variable BC is specified at the perimeter of the ASR well.

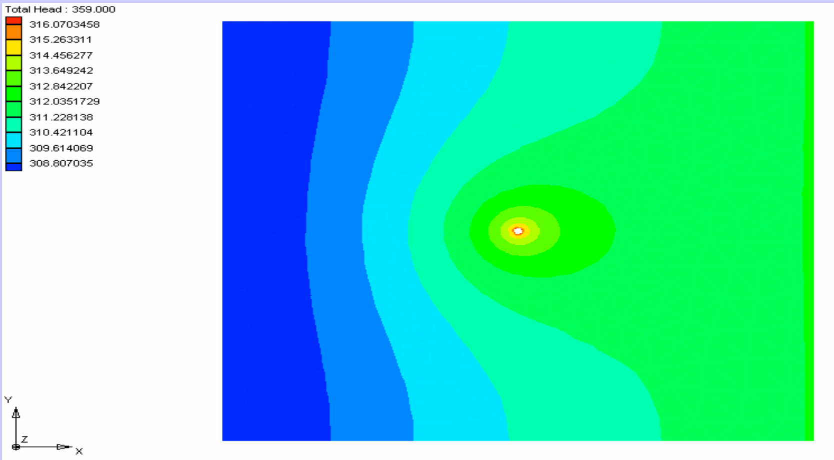
3D Mesh

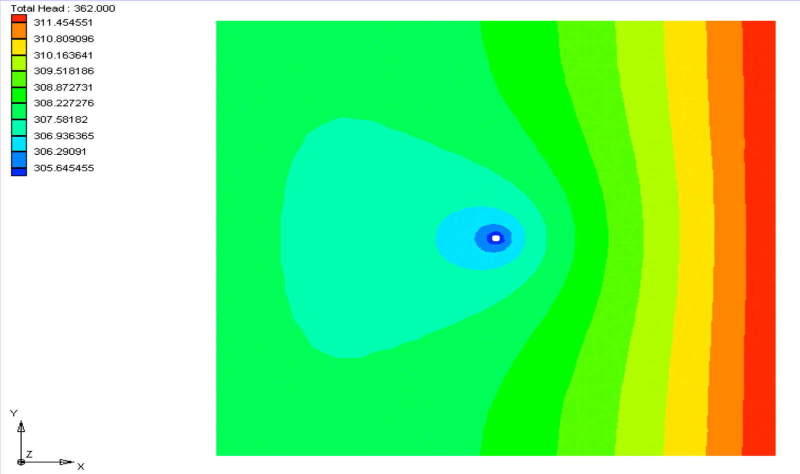
- The total number of nodes: 3,280
- The total number of elements: 4,674
- The size of elements is finest within the vicinity of the well.
- Three layers

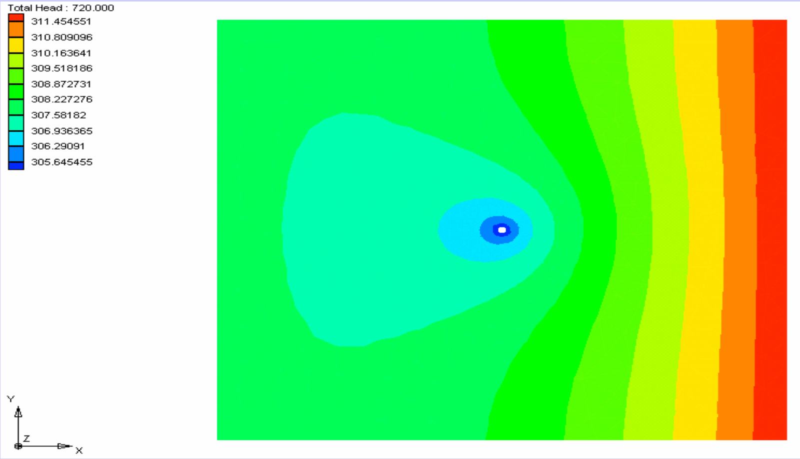


Total Head Distribution (t = 0, 359, 362, and 720 h)

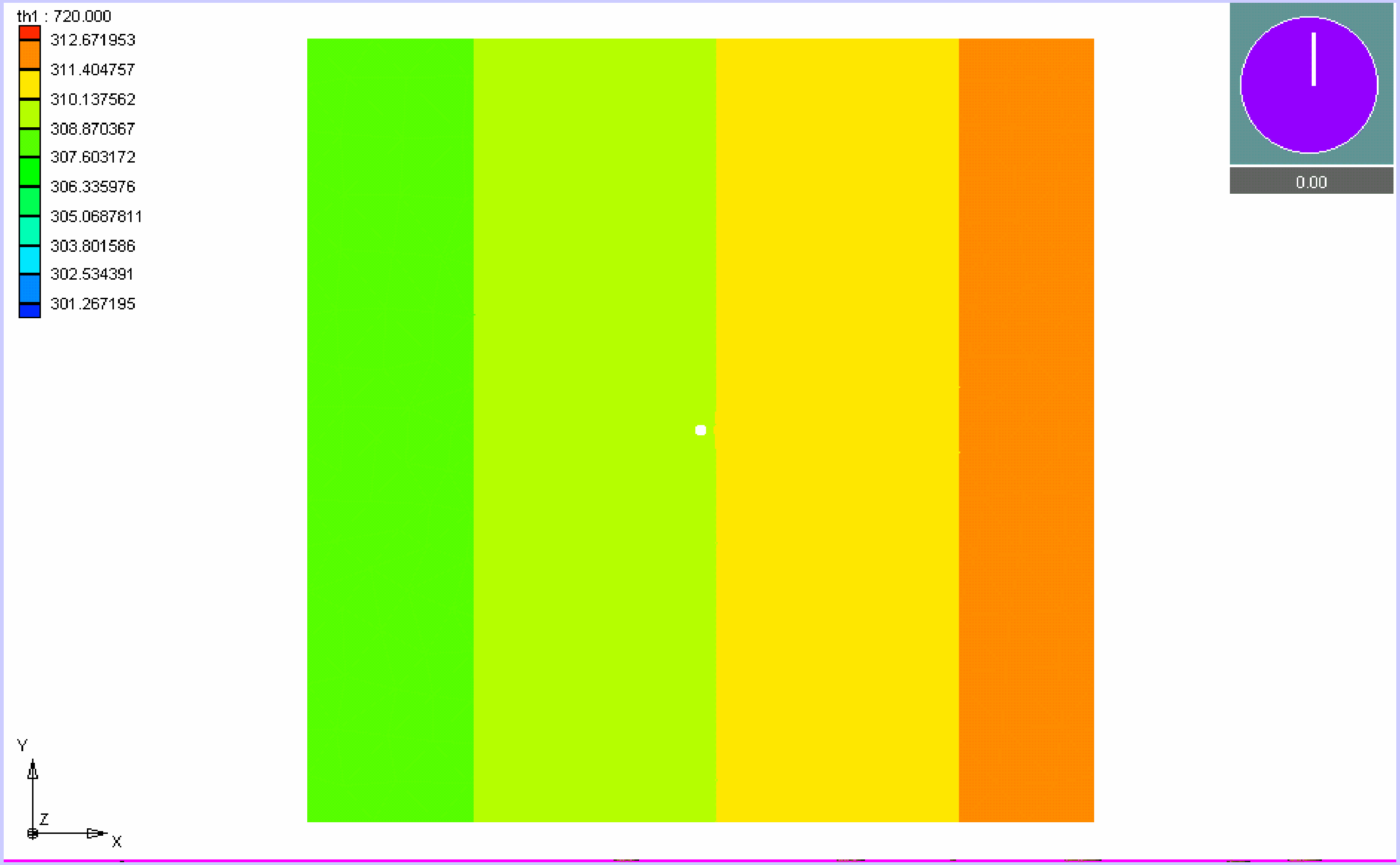




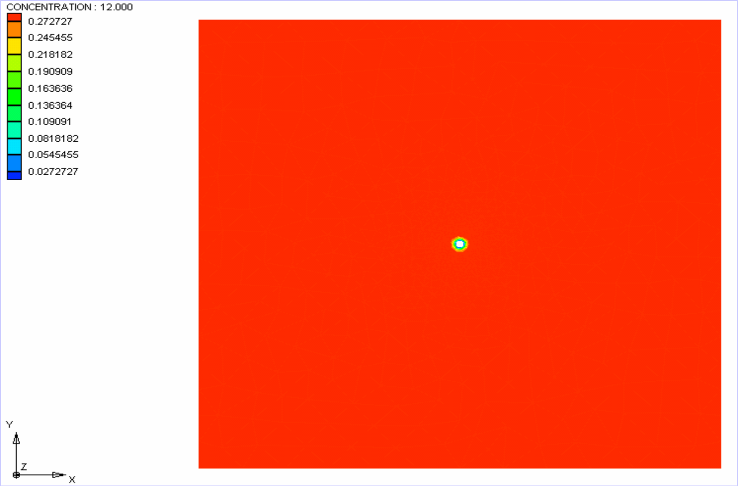


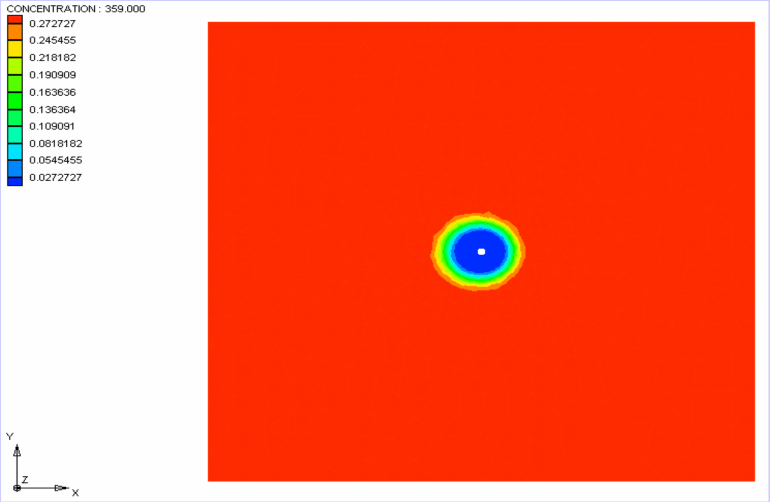


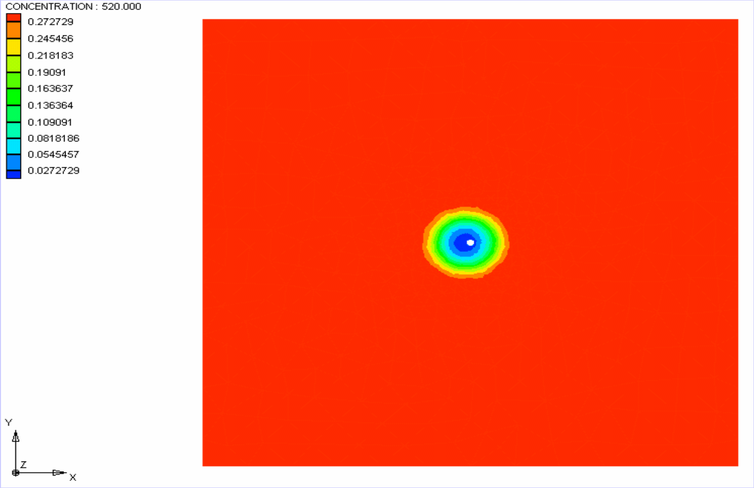
Total Head Animation (totalhead_unsysm.avi)

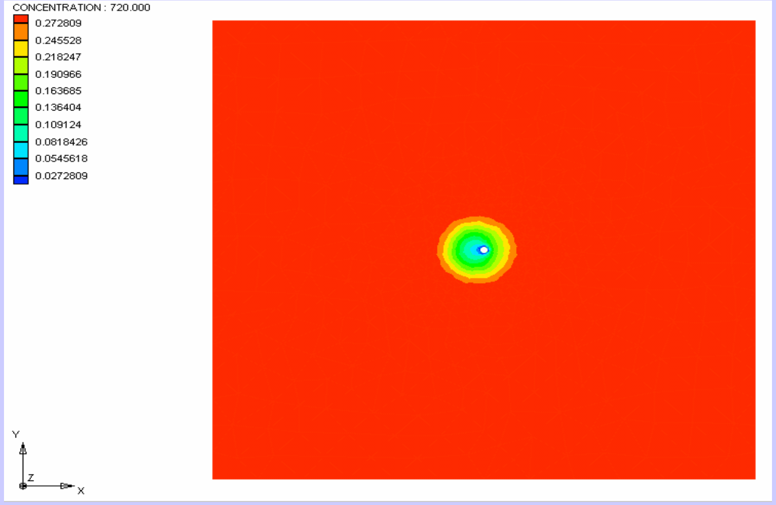


Concentration Distribution (t=12, 359, 520,500hr)

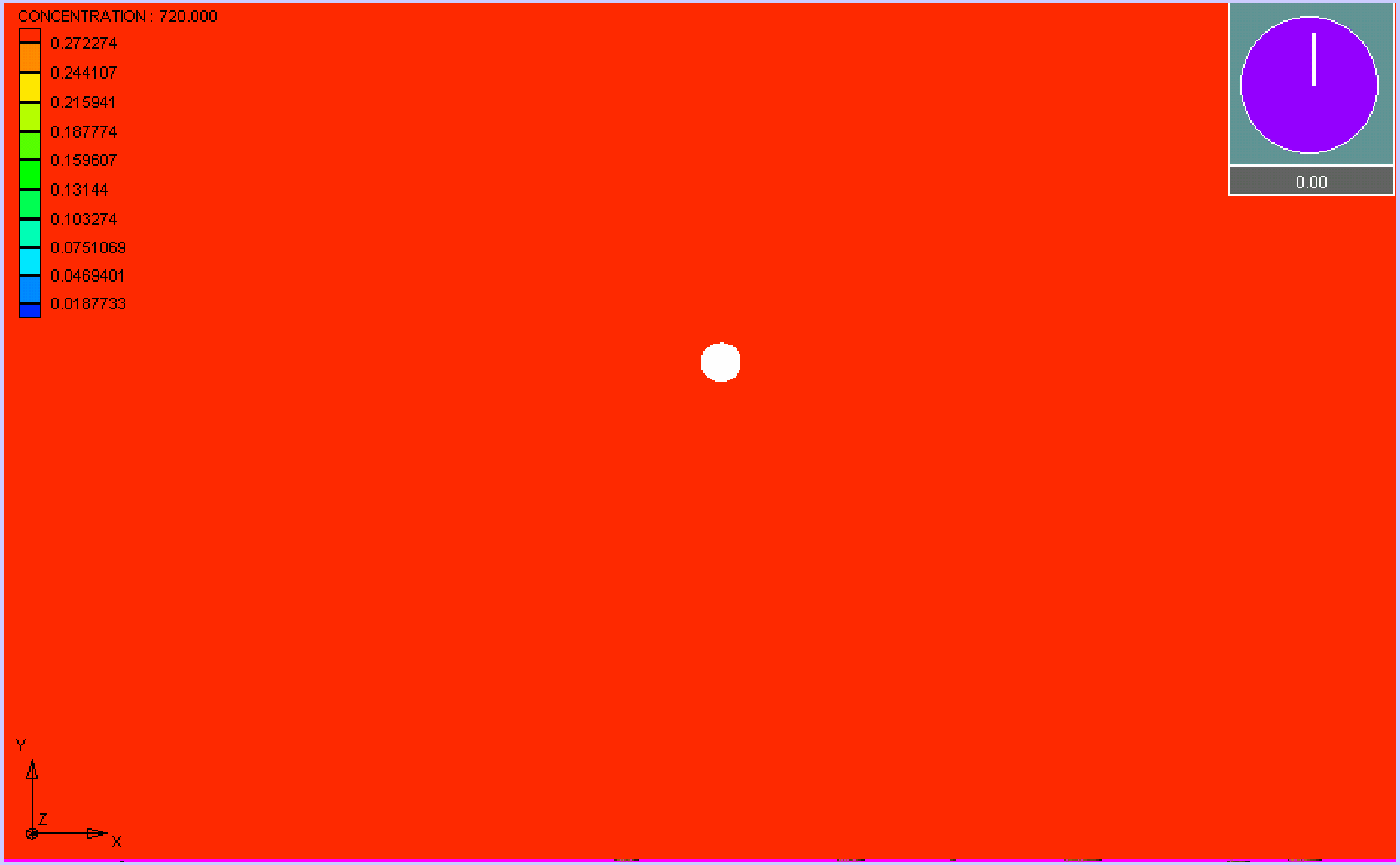








Concentration Animation (concentration.avi)



Example 2: South Fork Broad River Watershed

Problem description

- This is a natural watershed with spatial varied elevation and slope.
- With both the overland flow and stream network flow considered, we study the surface runoff response of this watershed to the spatial and temporal distribution of rainfall.
- Soil and vegetation, and land use data is limited, so this is only a preliminary test run.
- The watershed of this sub-basin is approximately 453 square kilometers.

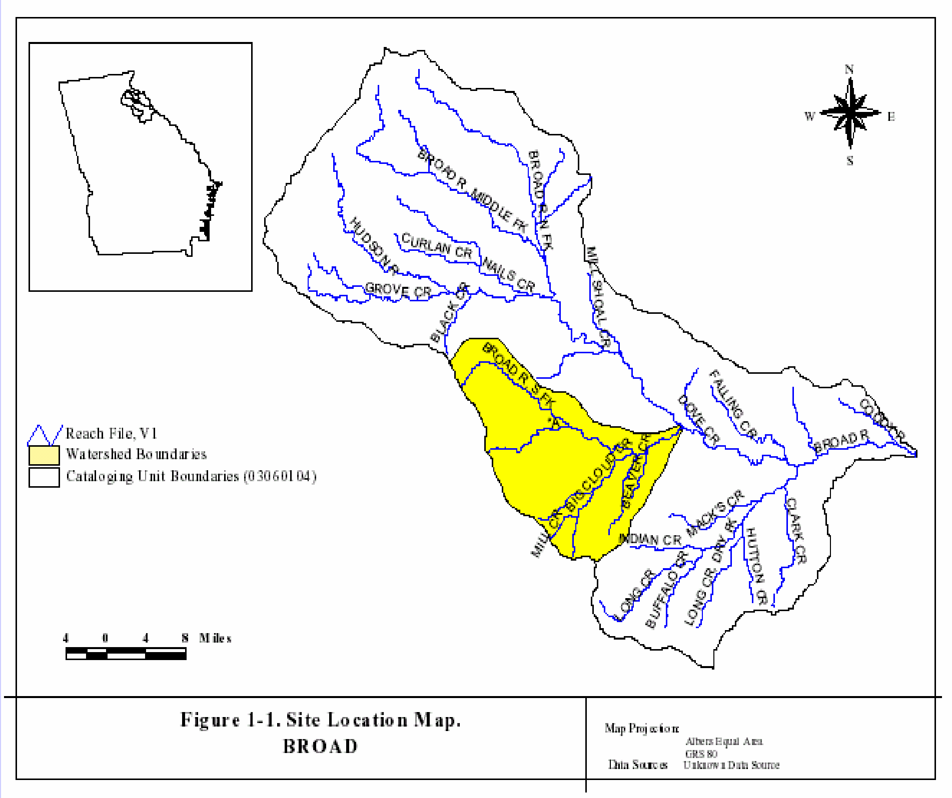
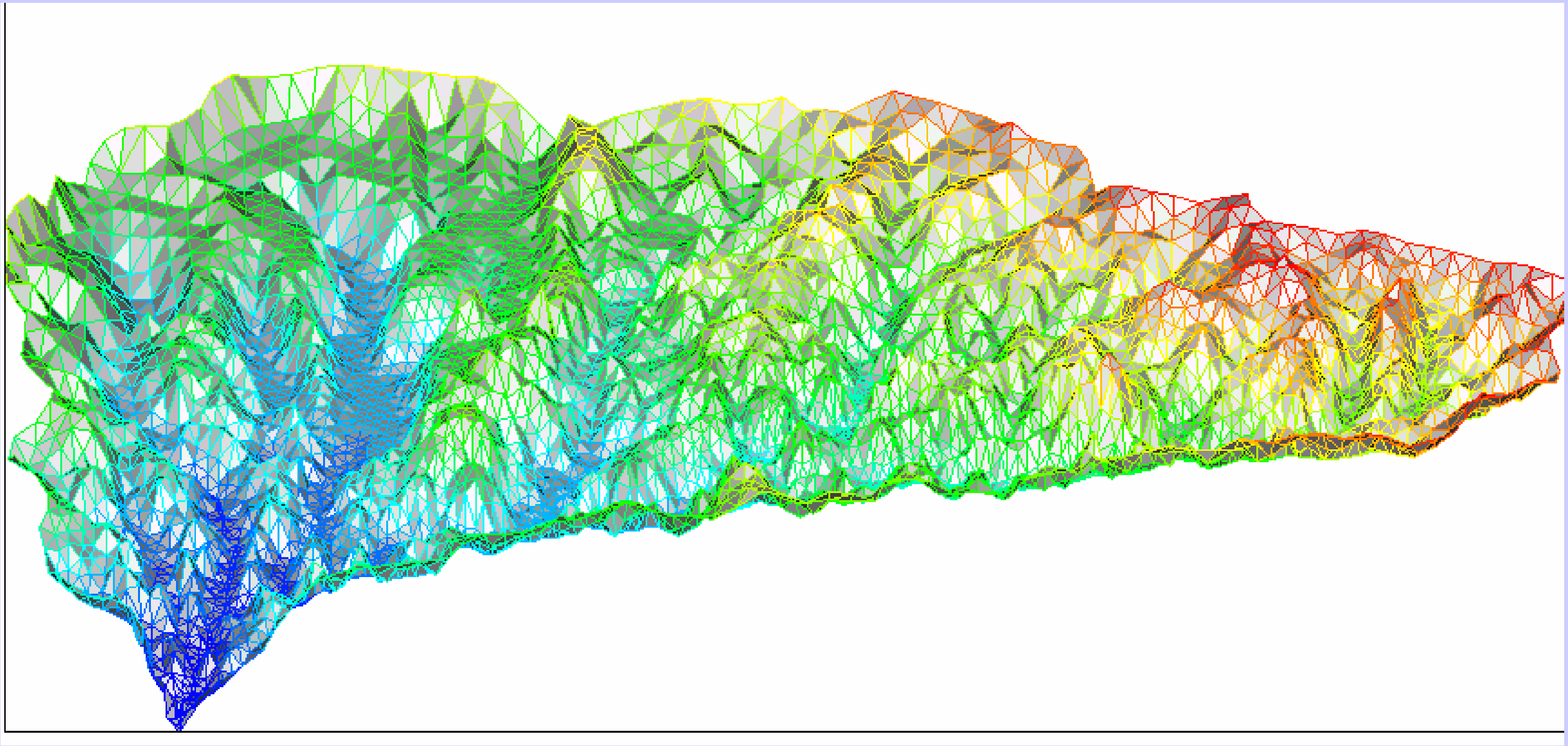


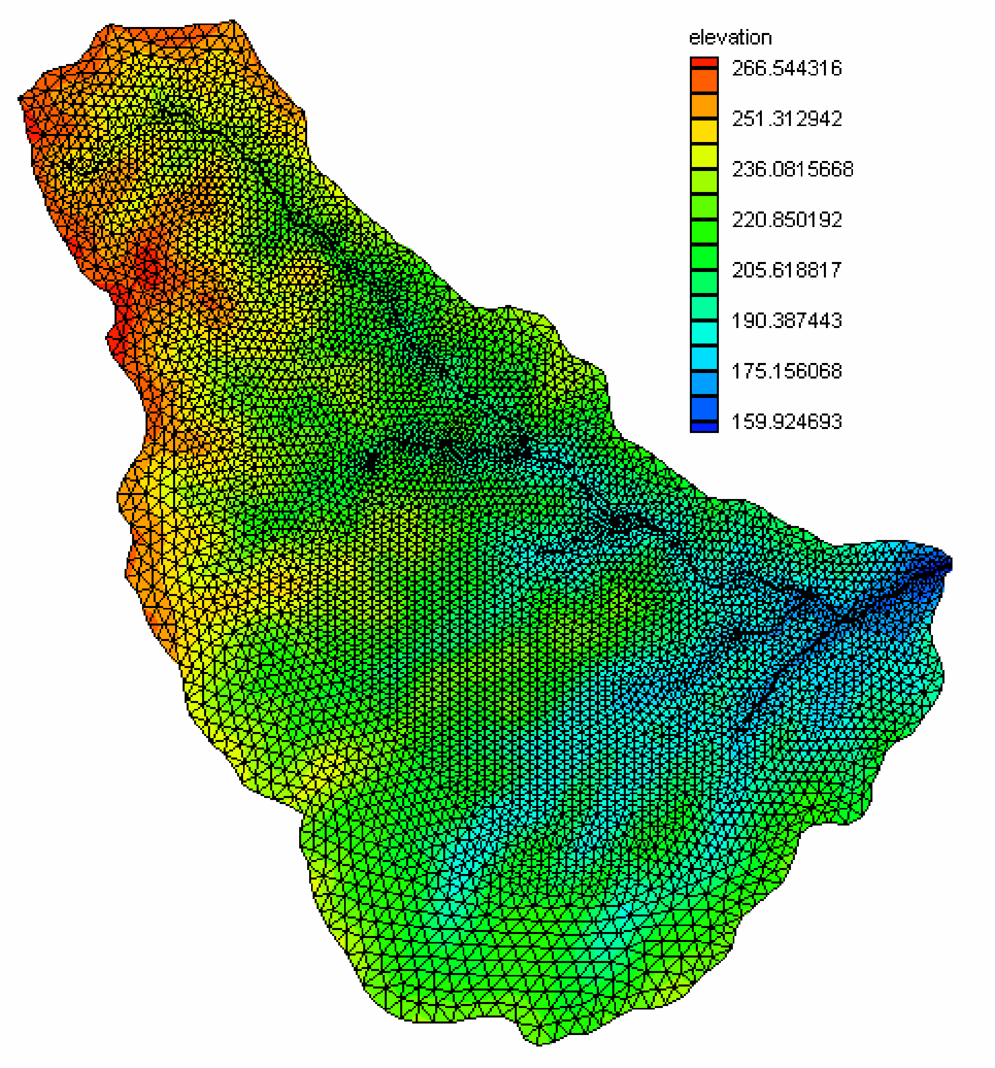
Figure 1-1. Site Location Map.
BROAD

- **This example involves the surface runoff and flow dynamics in stream network in the South Fork Broad River Tributary of Savannah River in South Carolina**
- **Local bottom slope along the x-direction is between -0.06 to 0.05; Local bottom slope along the y-direction is between -0.05 to 0.06.**

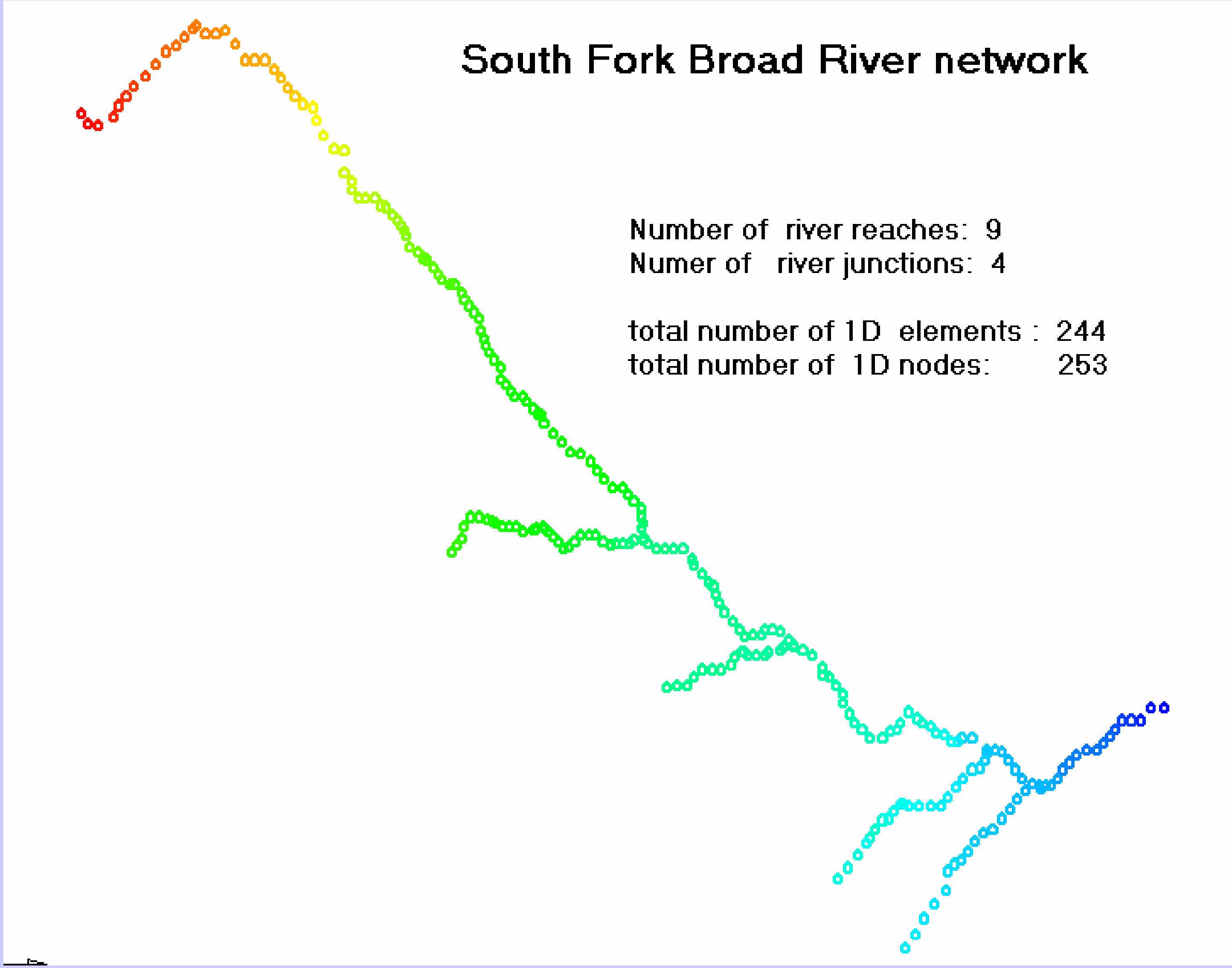


Finite Element Discretization

- Total number of 2D elements: 10,930
- Total number of 2D global nodes: 5,567
- Real time simulated: 63 hours



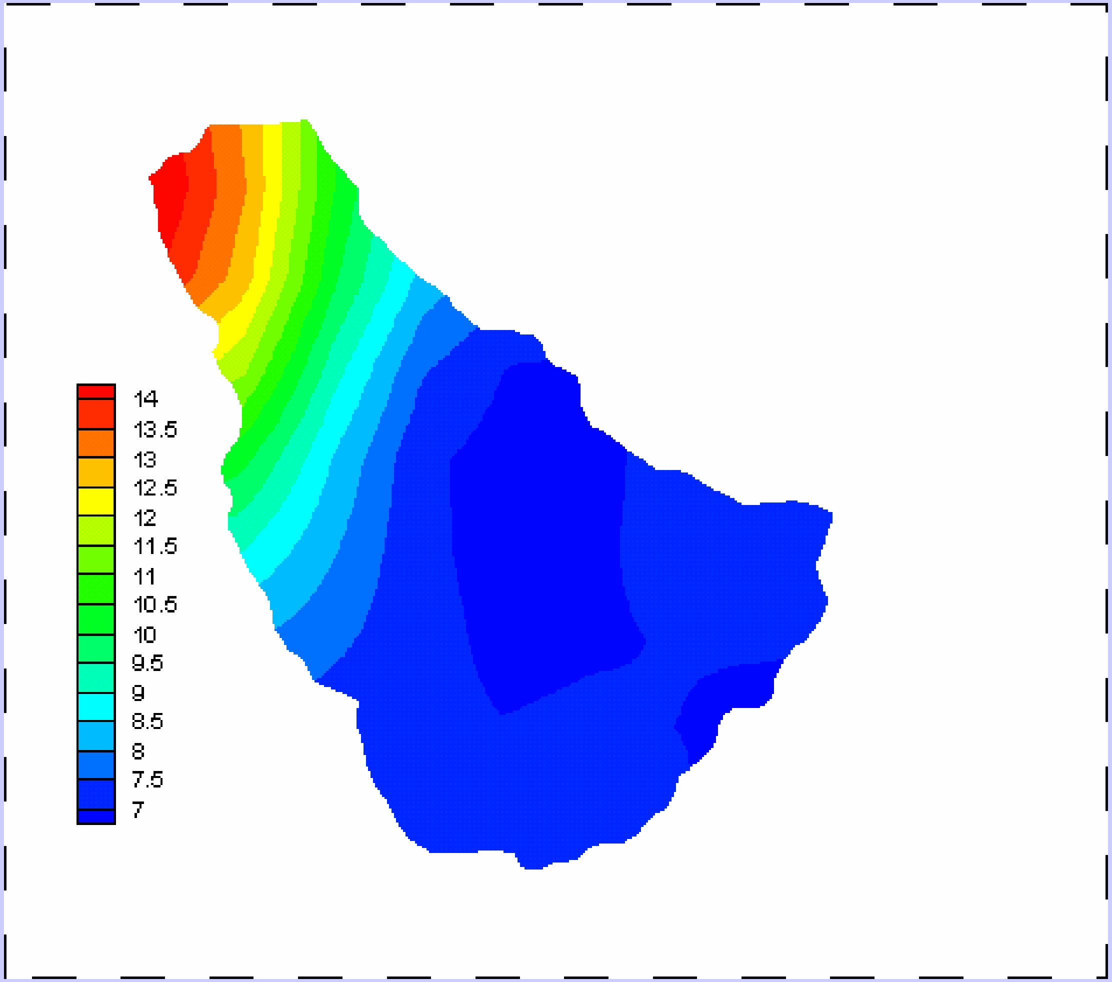
- **The river/stream network.**



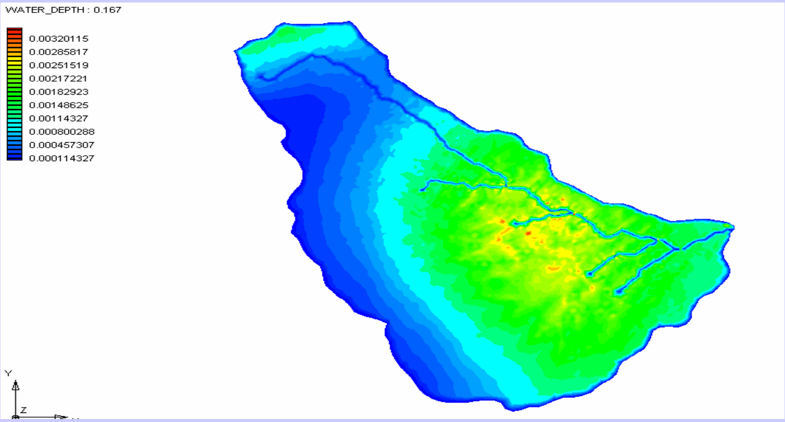
MM5 and Rainfall Prediction

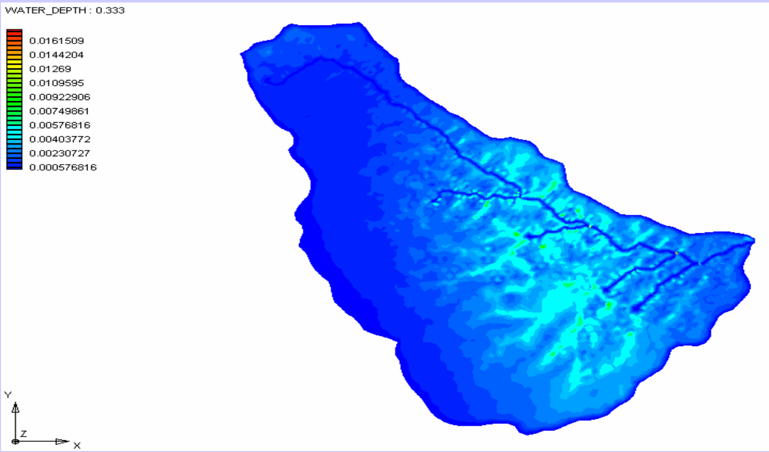
- **The Penn State/NCAR MM5 (version 3.4) was used to predict rainfall.**
- **The storm event: Hurricane Earl (3-5 Oct 1998).**
- **The grid size on Mercator projection are 135, 45, 15, and 5 km,respectively.**
- **The 5 km domain rainfall forecasts at 10-minutes intervals are used in WASH123D.**
- **Rainfall forecast data (10-minute intervals) were interpolated to each triangular element mesh.**

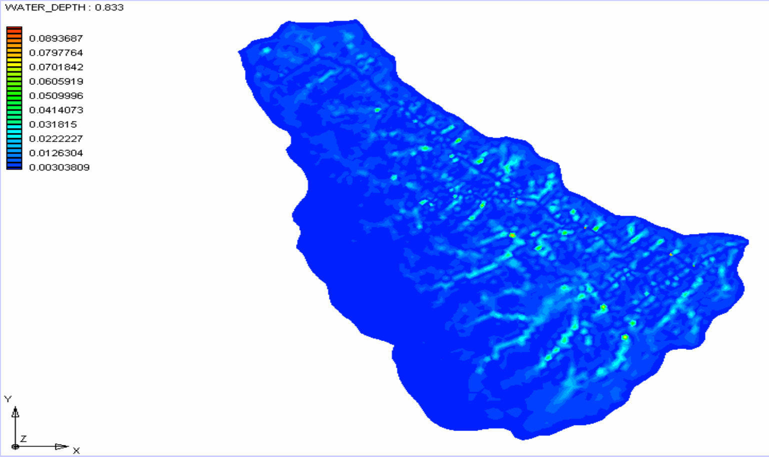
- **The 24-hour accumulated rainfall forecast for the SFB watershed**

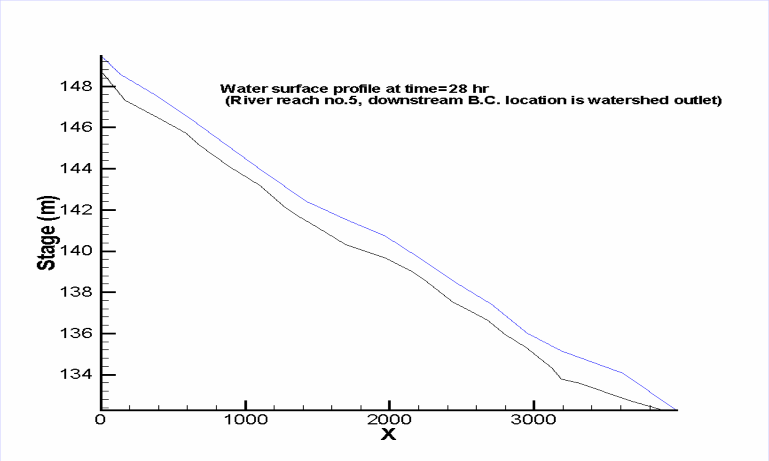


- **Water depth at various times (0.167, 0.333, and 0.833 h) and**
- **Stage profile in river reach no. 5 at time t = 28 h**

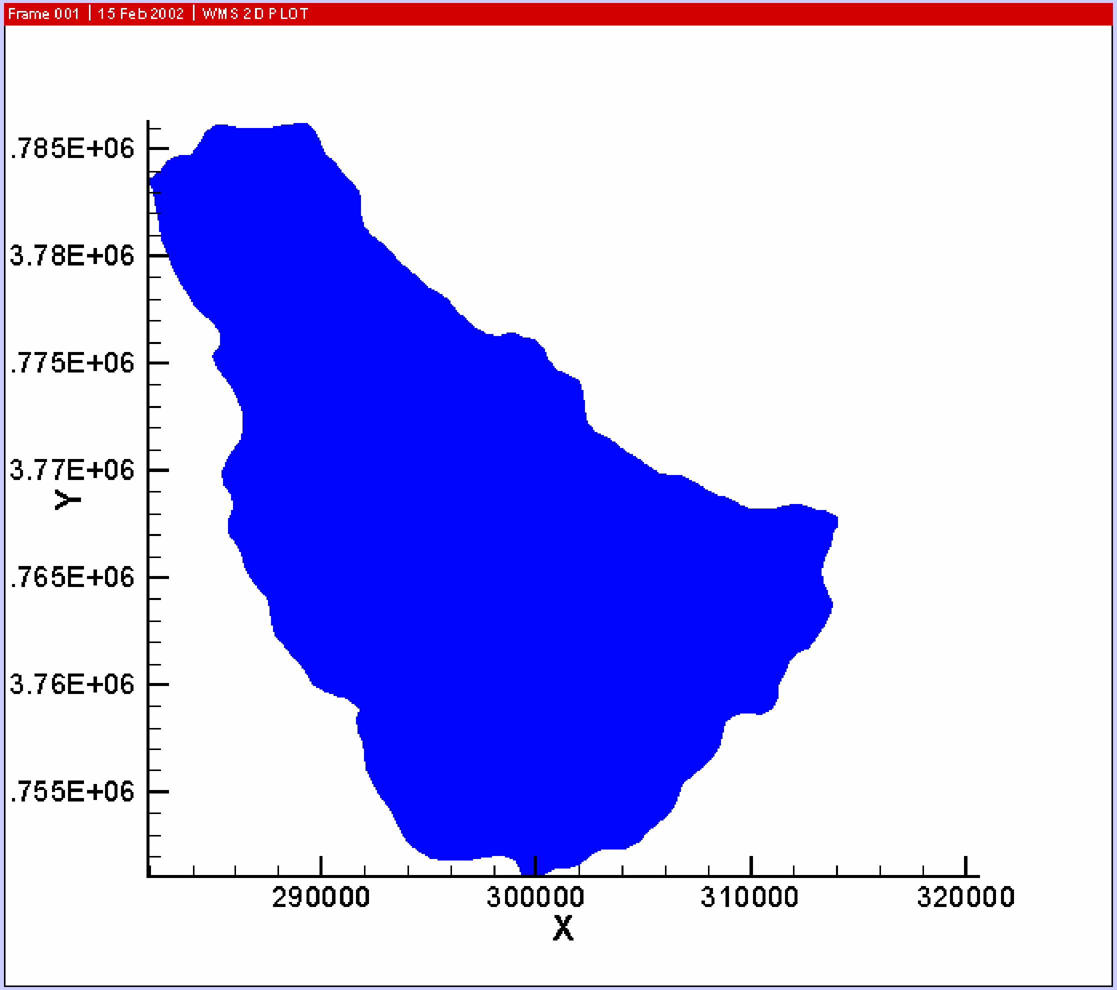




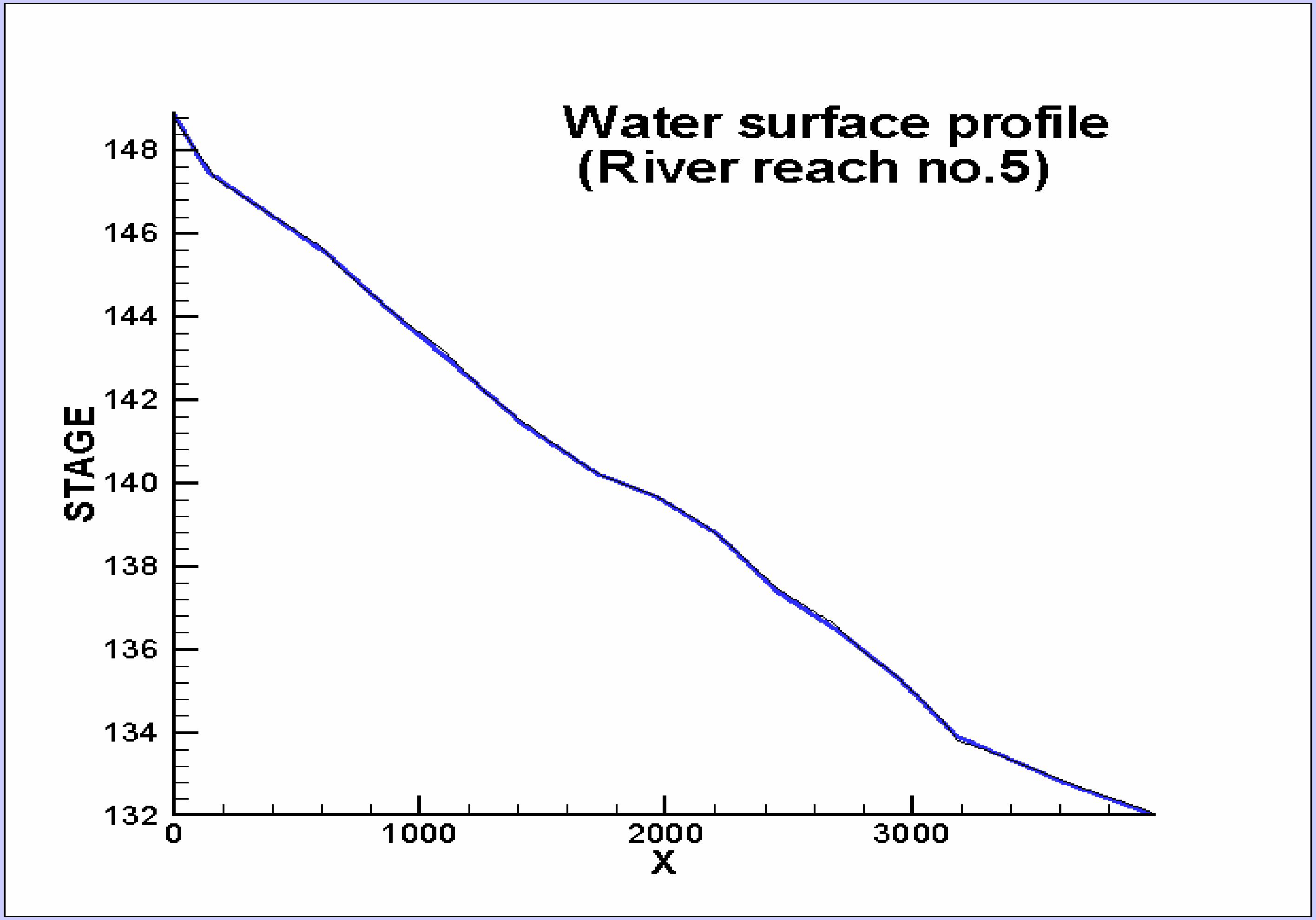




- **Animation of water depth from flooding (sfb12d63hr.avi)**



- **Animation of water depth from flooding (sfb-stgrh5.avi)**



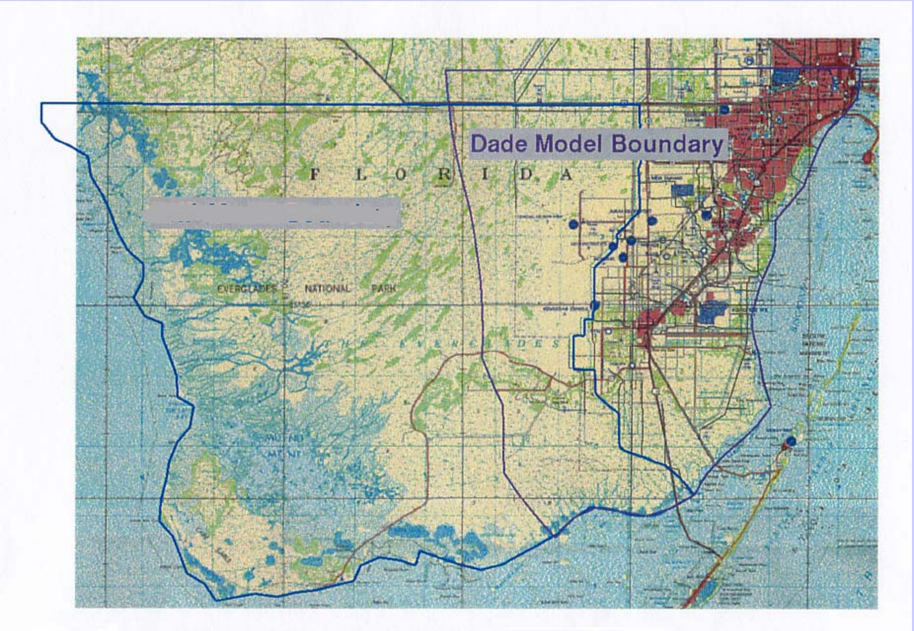
Example No. 3:

Coupled 1D, 2D, and 3D Flow in Dade County in South Florida

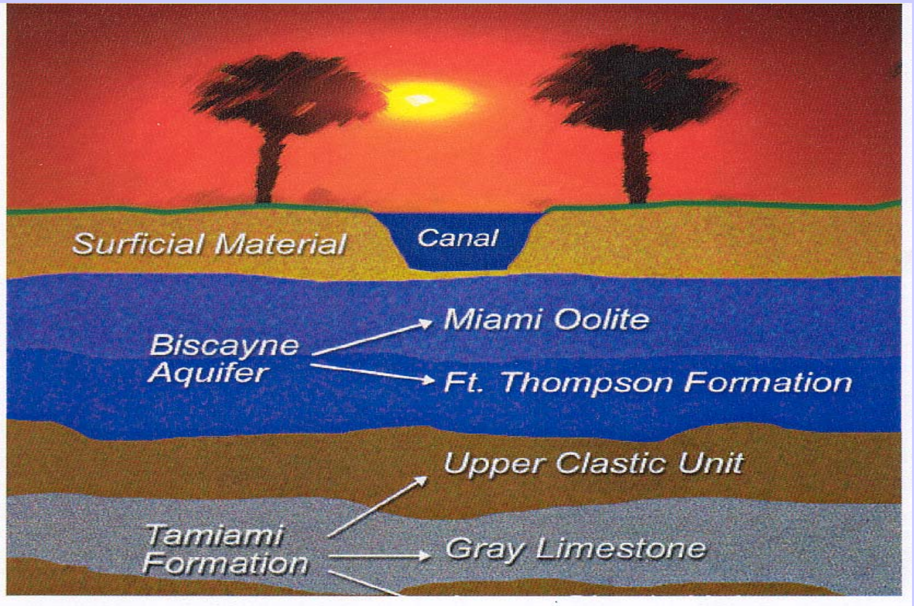
- **This problem involves the hydrology in coupled canal network, overland regime, and subsurface media in Dade county in South Florida.**
- **The problem presents numerical modeling challenges because the South Dade area has a thick vadose zone that is widespread and has great vertical relief, particularly in the coastal ridge area.**
- **When coupled with the numerous canals and hydraulic structures in the South Dade area and the high hydraulic conductivity of the subsurface, the hydrologic simulation problem becomes very complex.**

Problem description

- Dade model is a large scale regional problem.
- The model domain extends from four miles west of the L-67 Extension dike to the western shore of Biscayne bay and from one mile north of the Tamiami canal south to Florida bay. Vertically, it extends from the land surface to the bottom of the surficial aquifer.
- Strong interaction of overland flow/groundwater flow and canal flow in south Florida
- Complex hydraulic structure operations;



South Florida Project Boundaries for Dade Model



Boundary Conditions

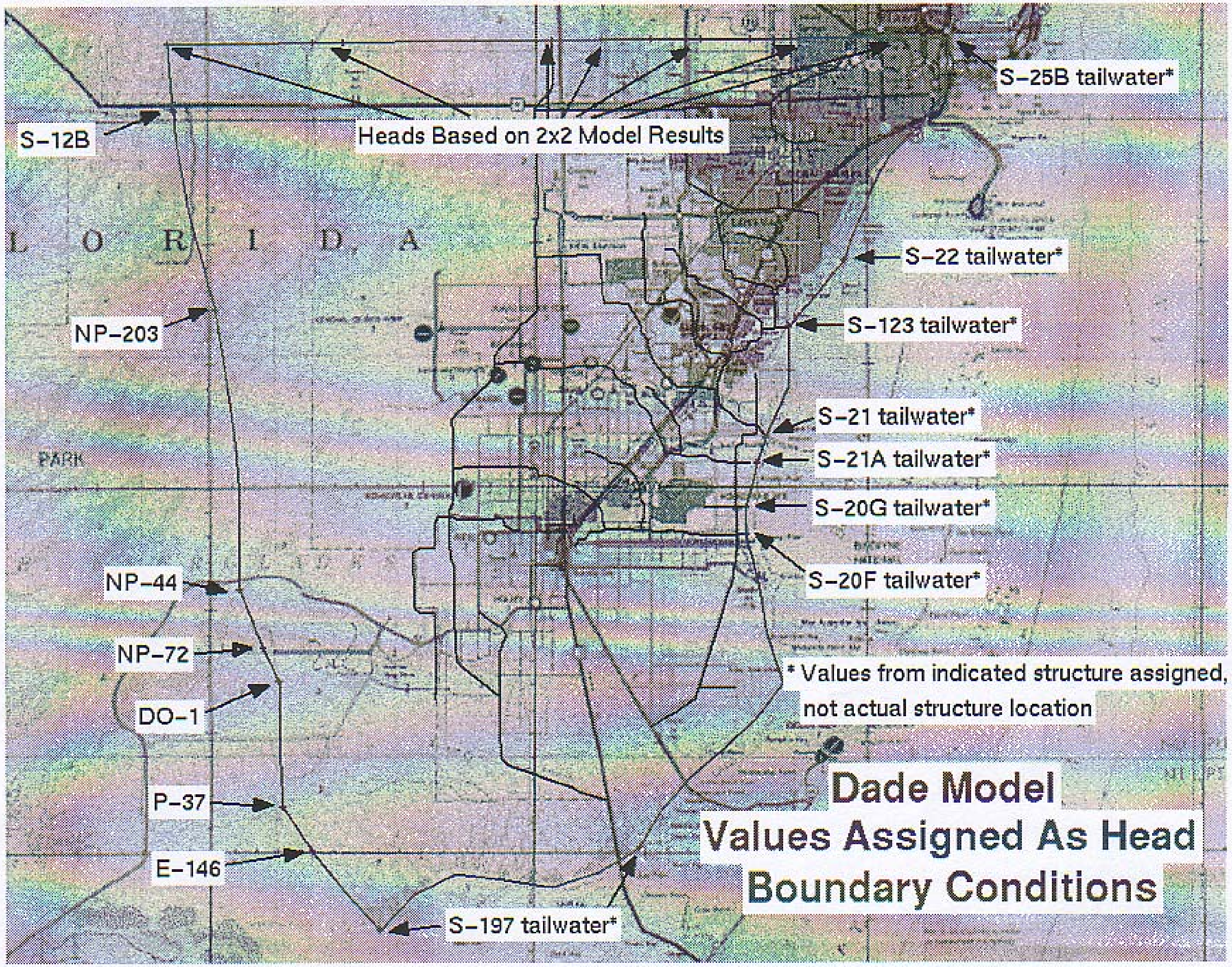


Figure 28 – Dade Model Head Boundary Condition Assignments

- There are 7 layers in vertical direction: **37,760 nodes, 65,429 elements.**
- Levees are incorporated as part of subsurface media.
- Real Time Simulated: 22 days

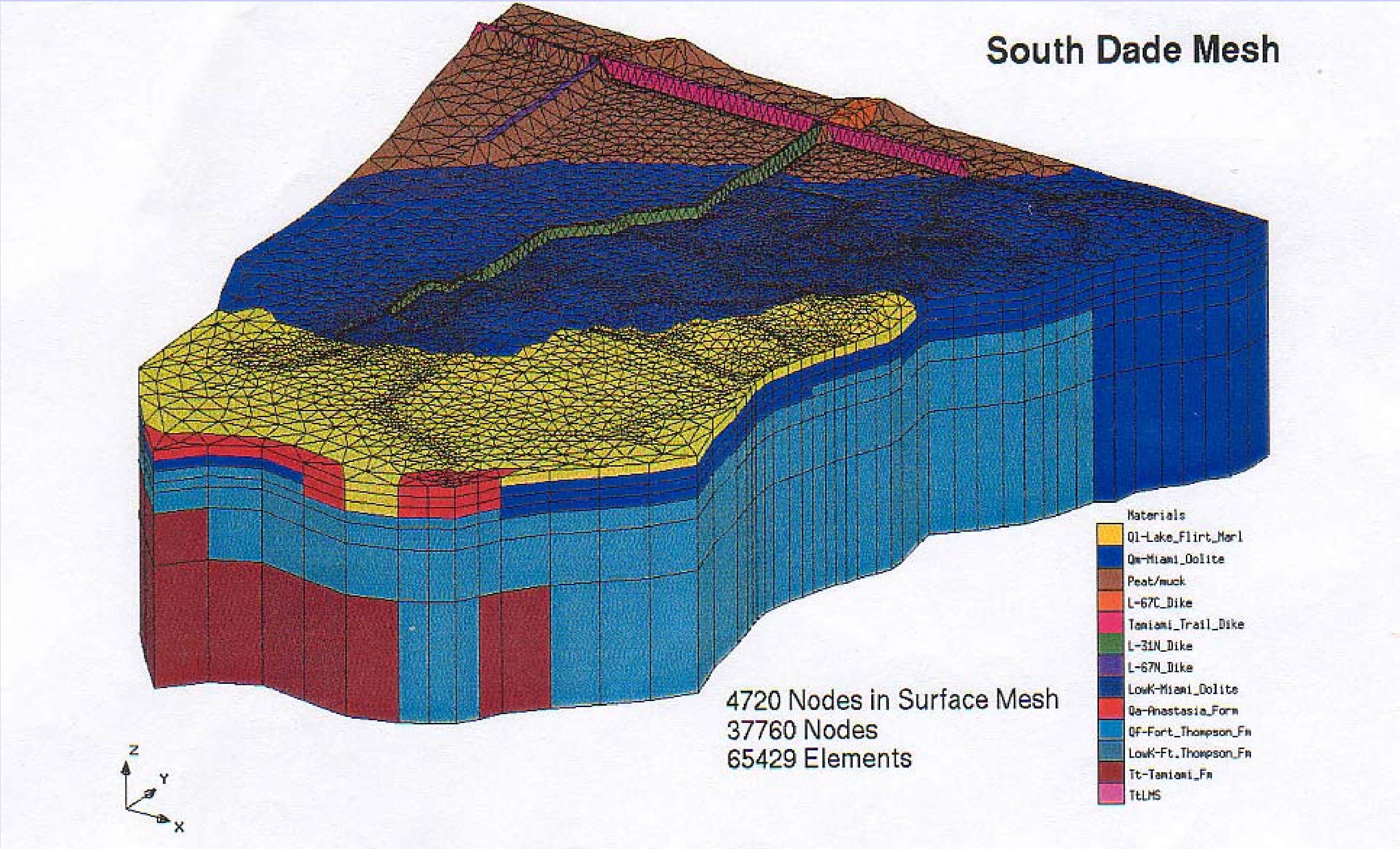
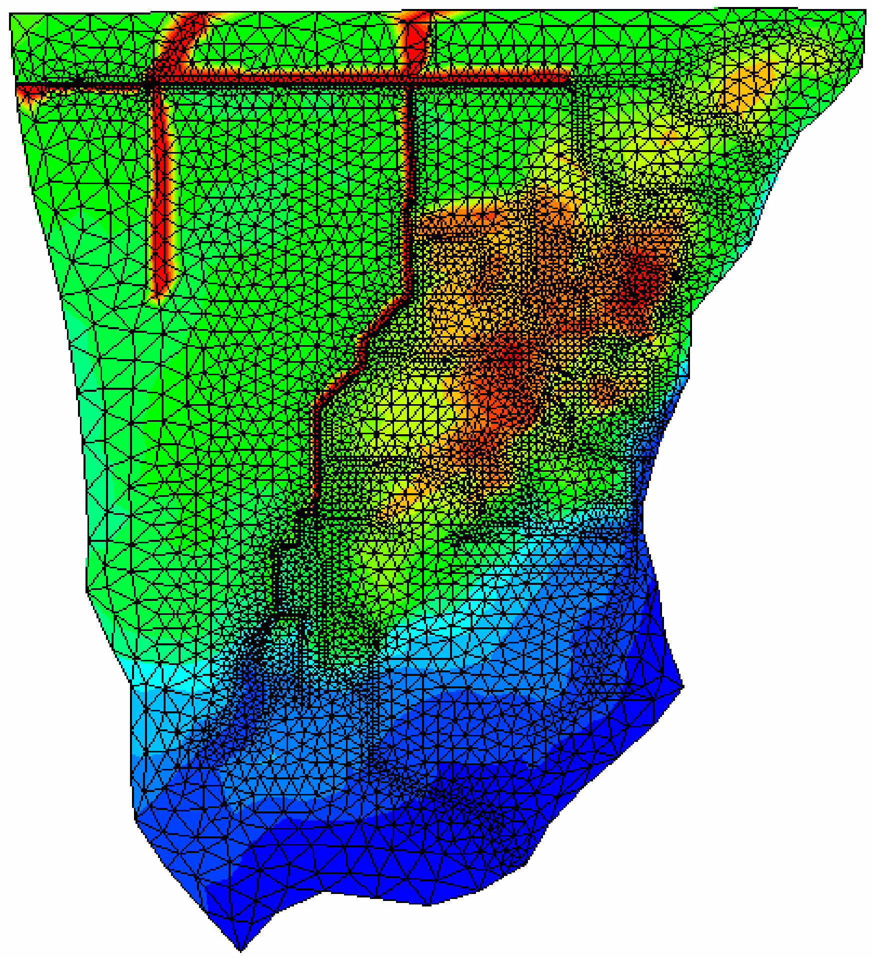
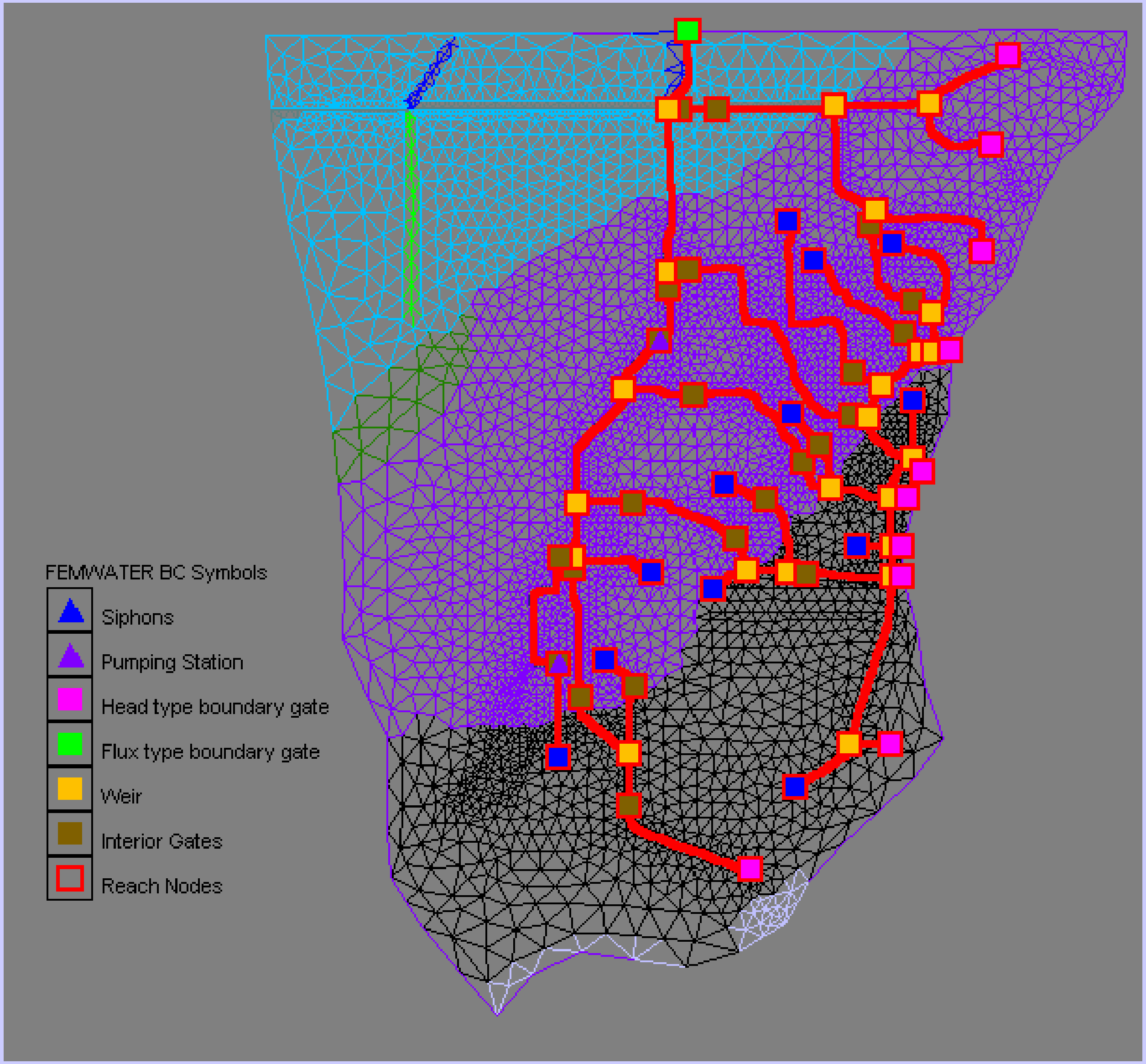


Figure 25 – Dade Model 3D Finite Element Mesh with Materials

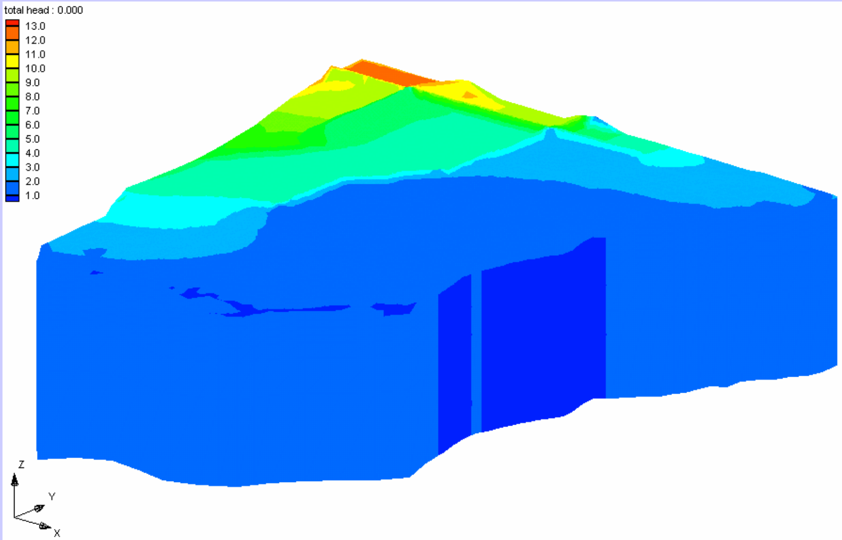
- **2D Overland Mesh: 4,720 Surface Nodes**

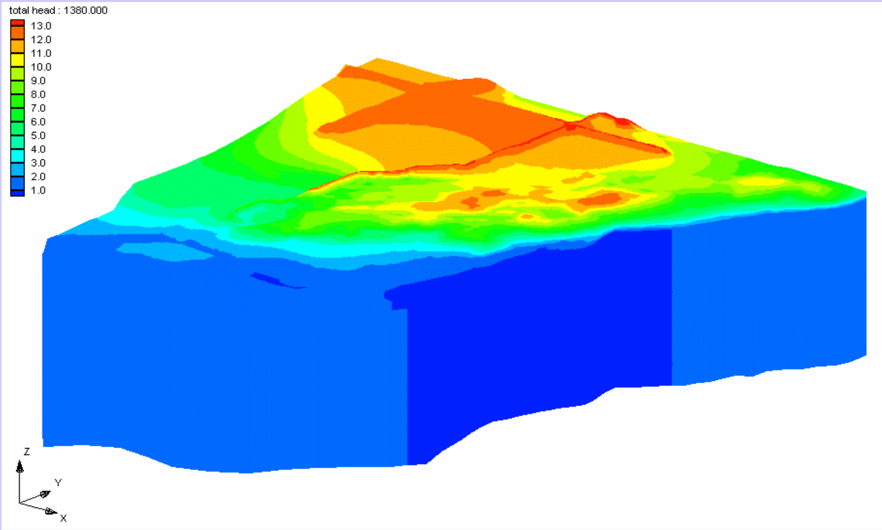


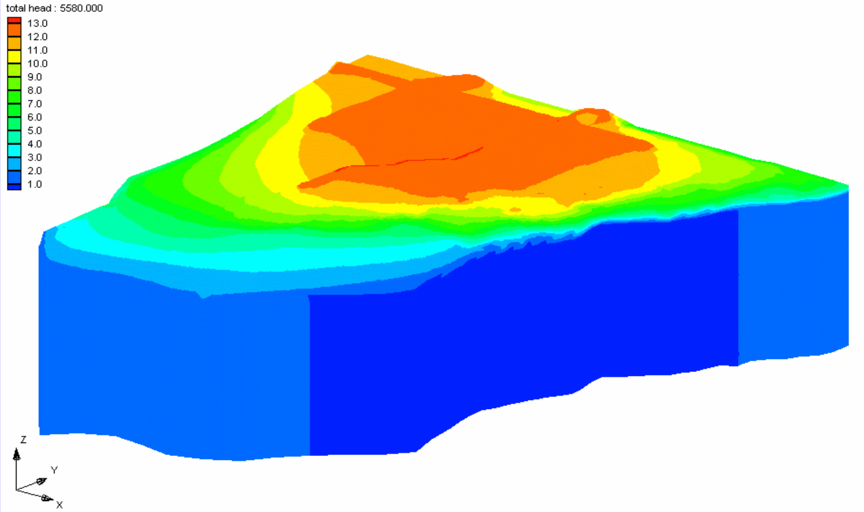
- **Canal Network with Structures**



- **Total Head Distribution at Various Time.**



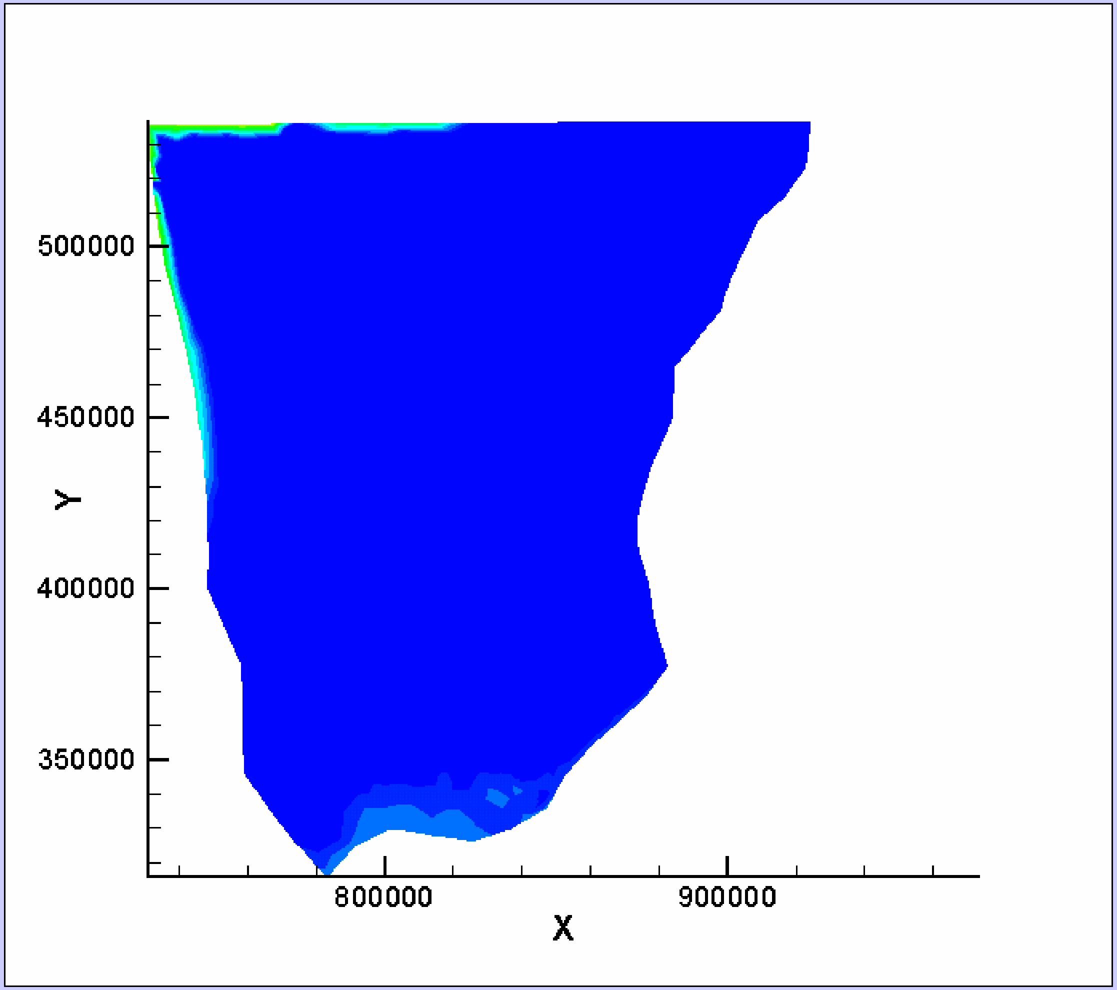




Total Head Distribution at time:

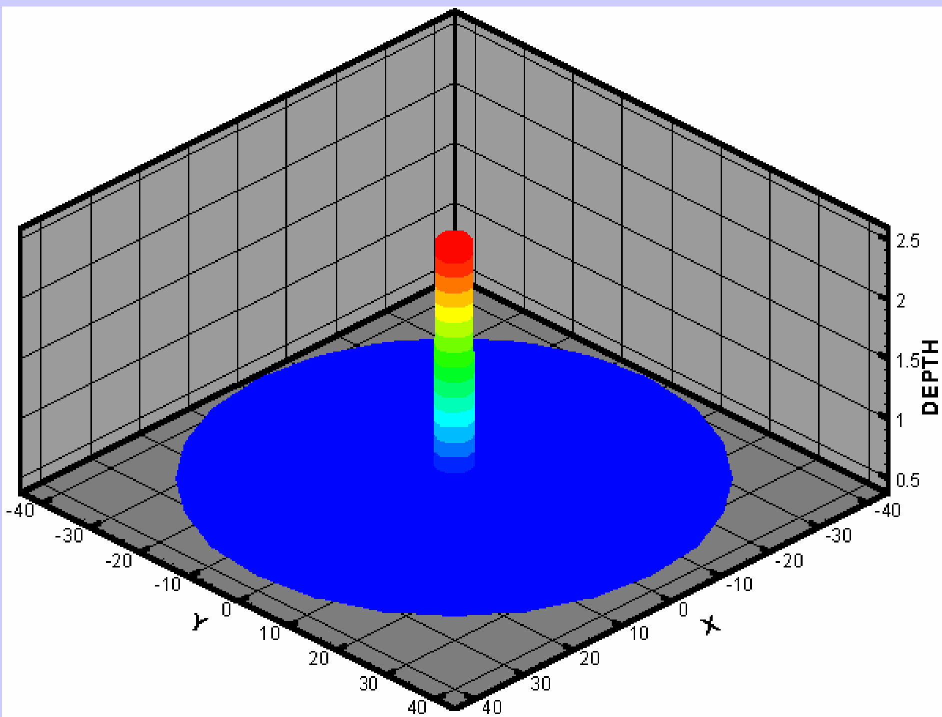
- (a) 0 hour (upper left)
- (b) 23 hours (upper right)
- (c) 93 hours (lower left)

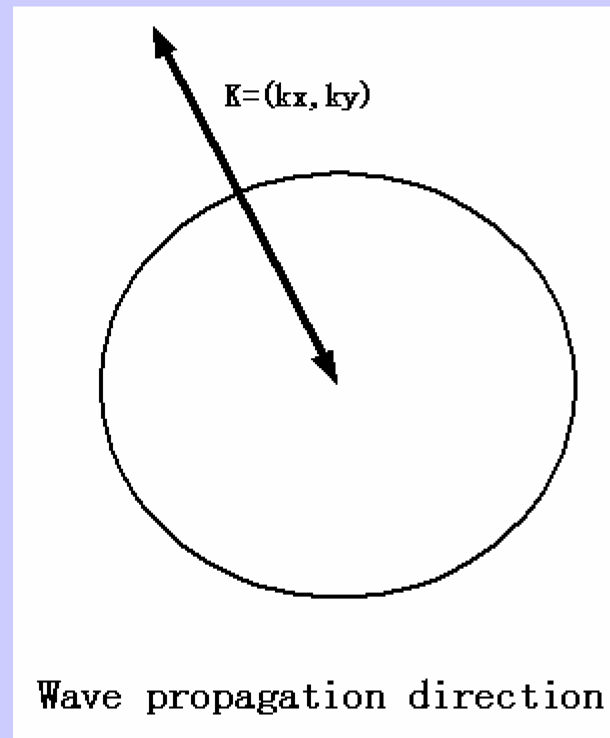
- **Animation of Water Depth in the Overland (dade2ddepth.avi)**



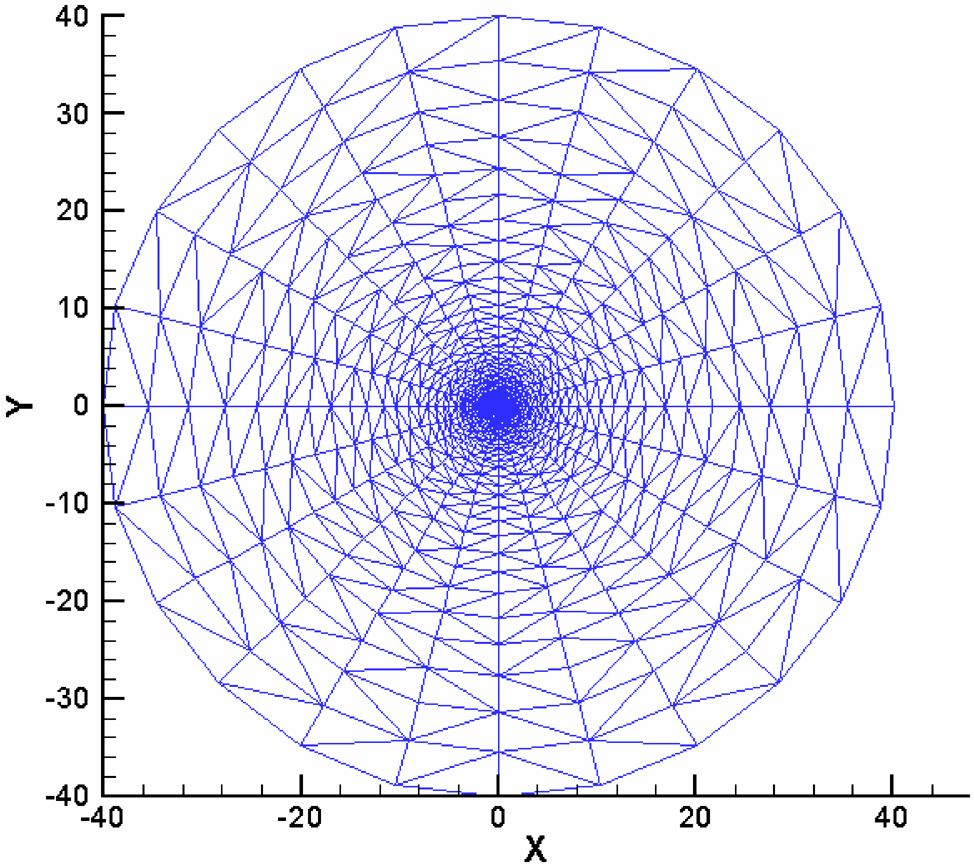
Example No. 4: Circular Dam Break Problem

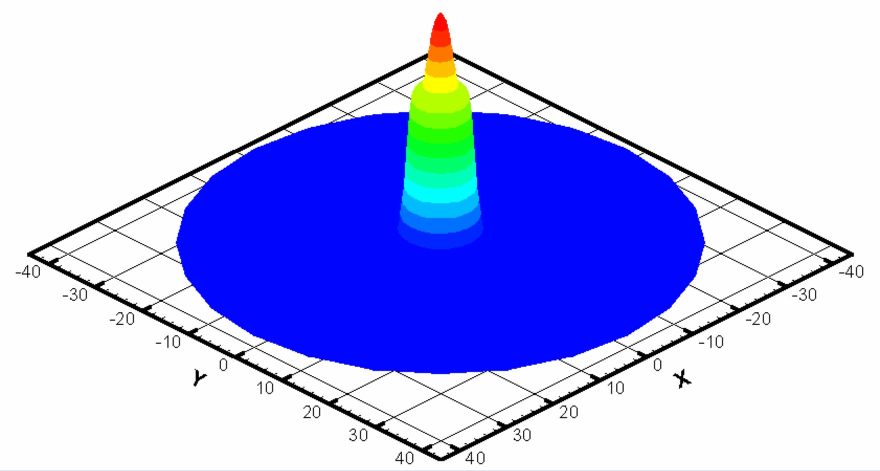
This is an idealized circular dam with frictionless Horizontal bottom, the entire circular thin wall with a Radius of 2.5 m has a sudden collapse instantaneously.   At time t=0, the water depth in the dam is h=2.5 m, and h=0.5 m otherwise.

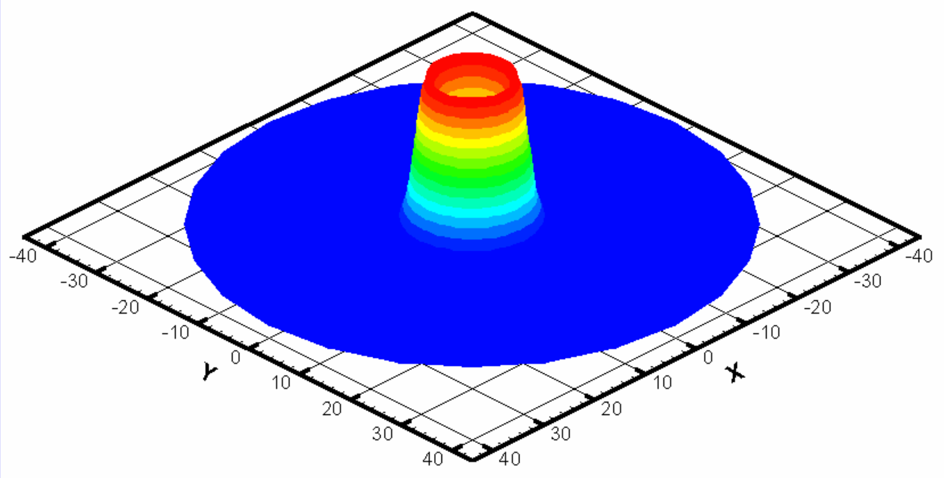


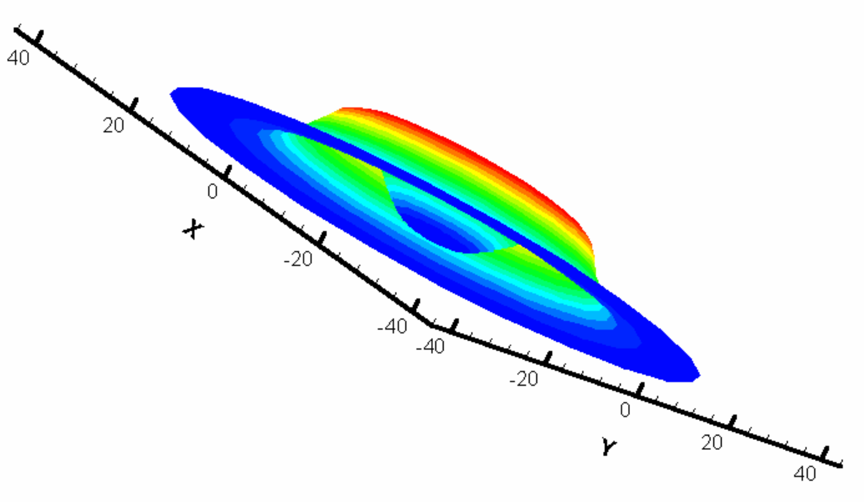


The computational mesh is composed of 2,854 triangular elements and 1,440 nodes. Only fully dynamic wave model can adequately simulate this problem, and 2-D MOC was applied .









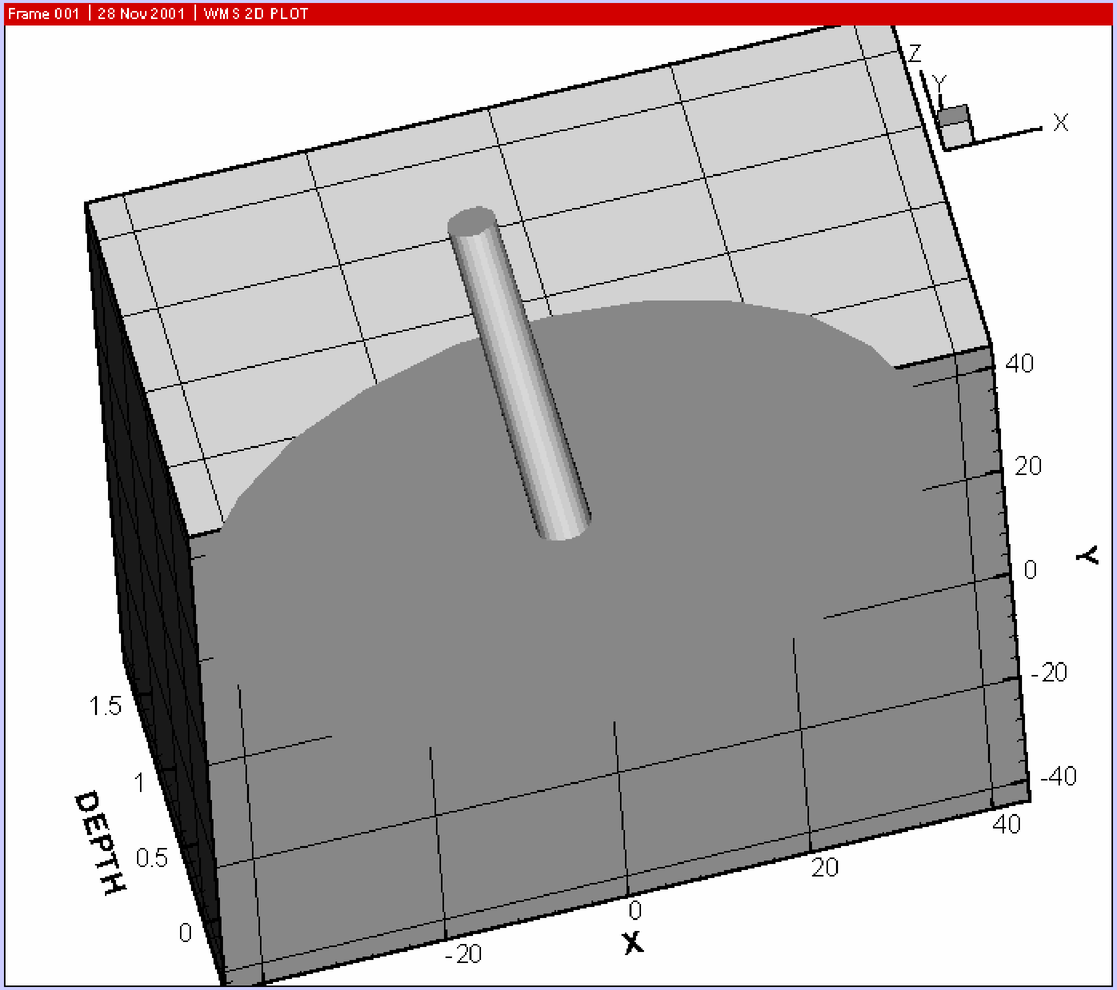
Water surface at various times:

(a) 0.7 s (Upper-Left)

(b) 1.4 s (Upper-Right)

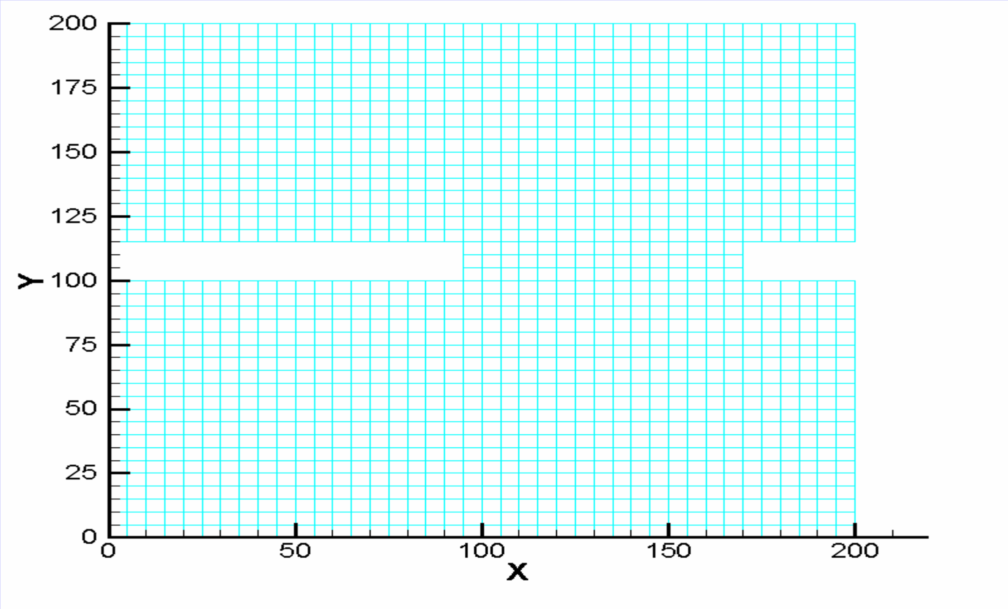
(c) 2.8 s (Lower-Left)

Animation (dambkcir.avi)

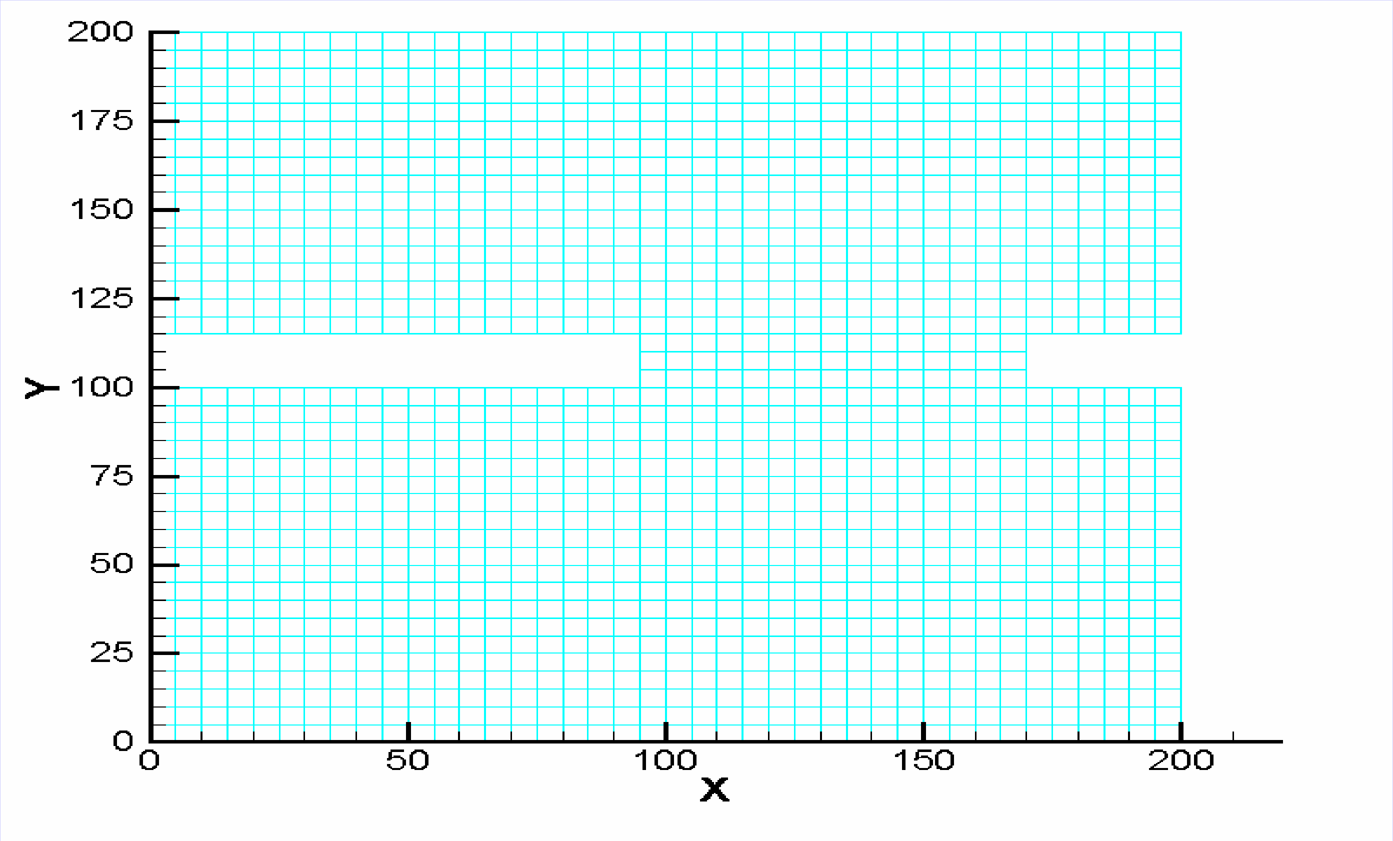


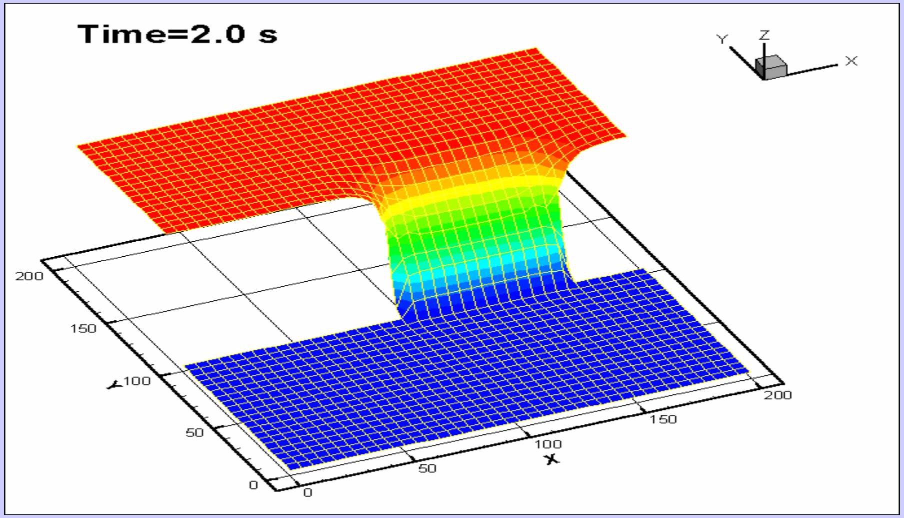
Example No. 5: 2-D Dam Break Problem

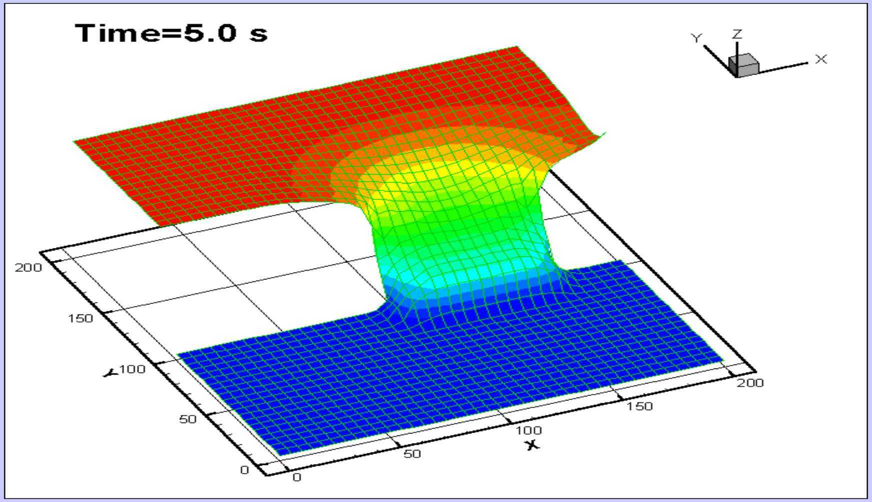
- This is a 2-D frictionless partial dam break problem as in Fennema and Chaudhry (1990) .
- The rectangular channel is horizontal with a dimension of (200 x 200 m)
- The breach is unsymmetrical. The width of the breach is 75 m, between x = 95 m to 170 m;
- The initial water depth is 10 m in the reservoir, and 0.05 m in the downstream. So this is a dry bed simulation, very difficult to be solved numerically by conventional FDM and FEM.

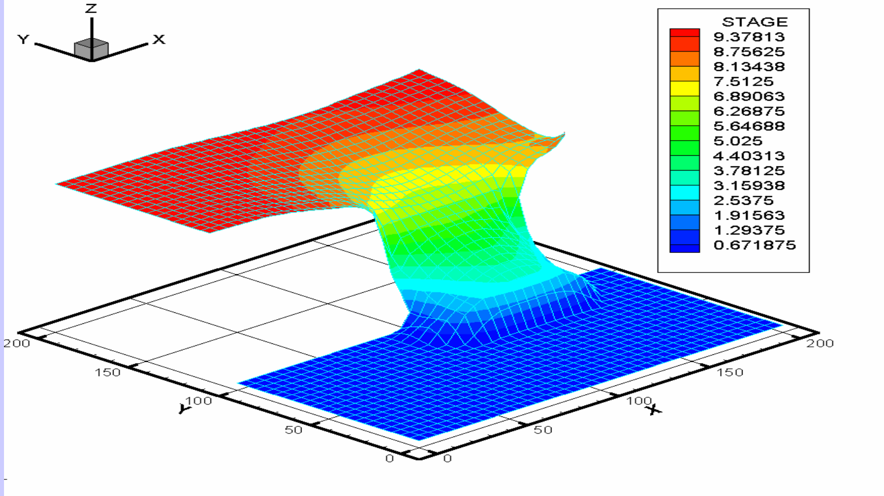


- The domain was divided into (5 x 5) m rectangular elements.
- The 2-D fully dynamic wave model was applied to this problem and solved by the Method of Characteristics(MOC).
- A time step of 0.15 s was used.









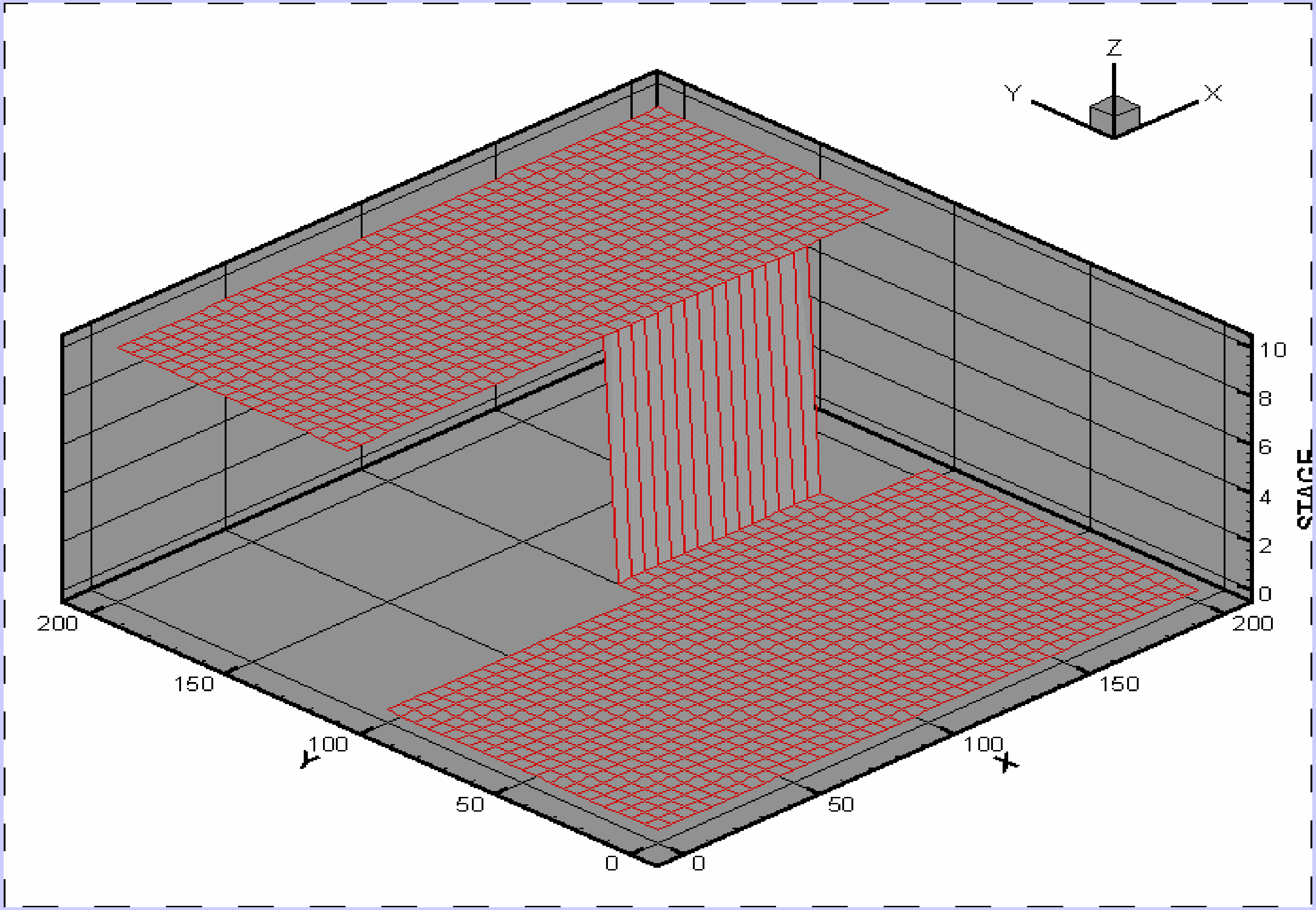
Water surface at various times:

(a) 2 s (Upper-Left)

(b) 5 s (Upper-Right)

(c) 7 s (Lower-Left)

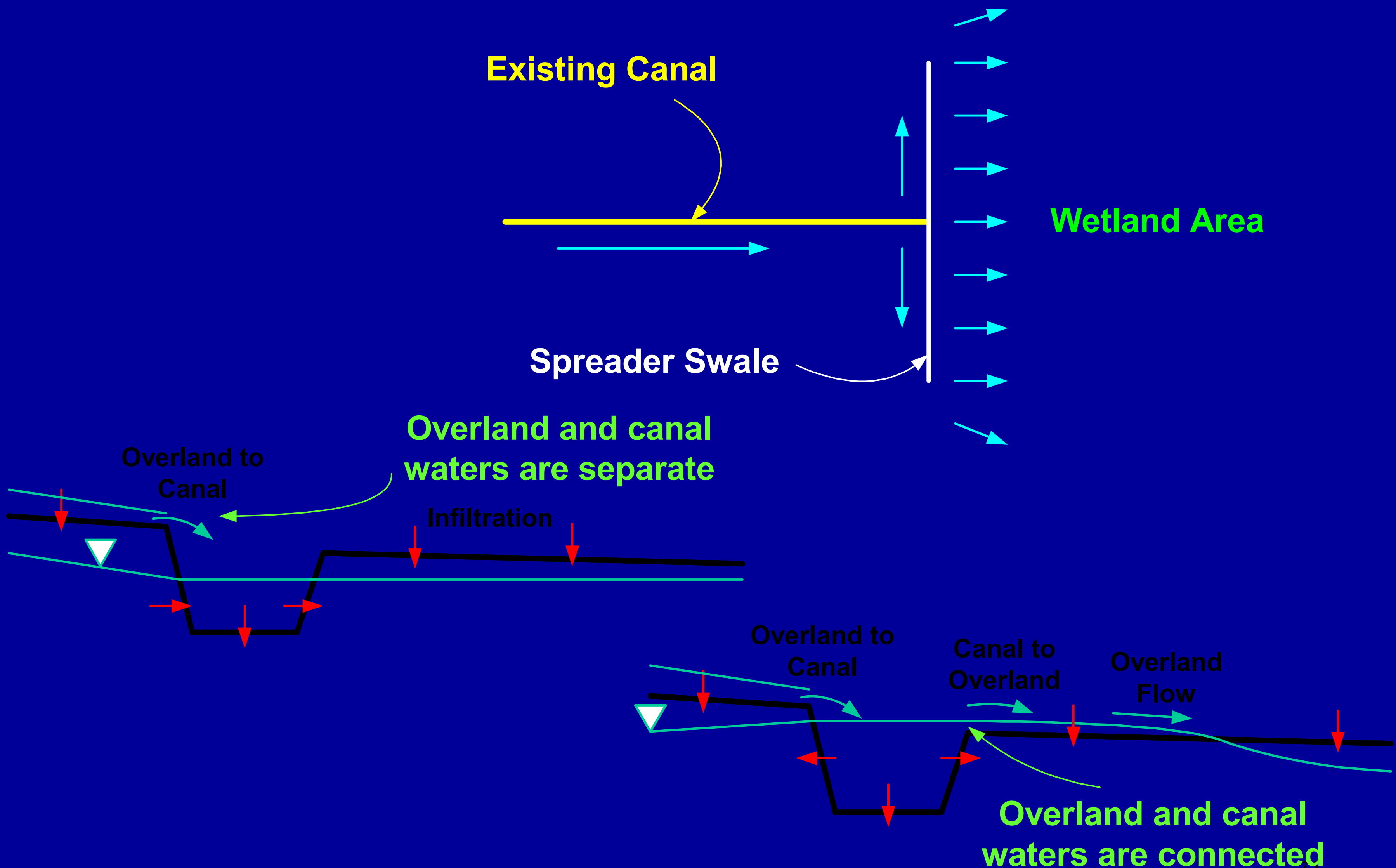
Animation (dambk2d_dry.avi)



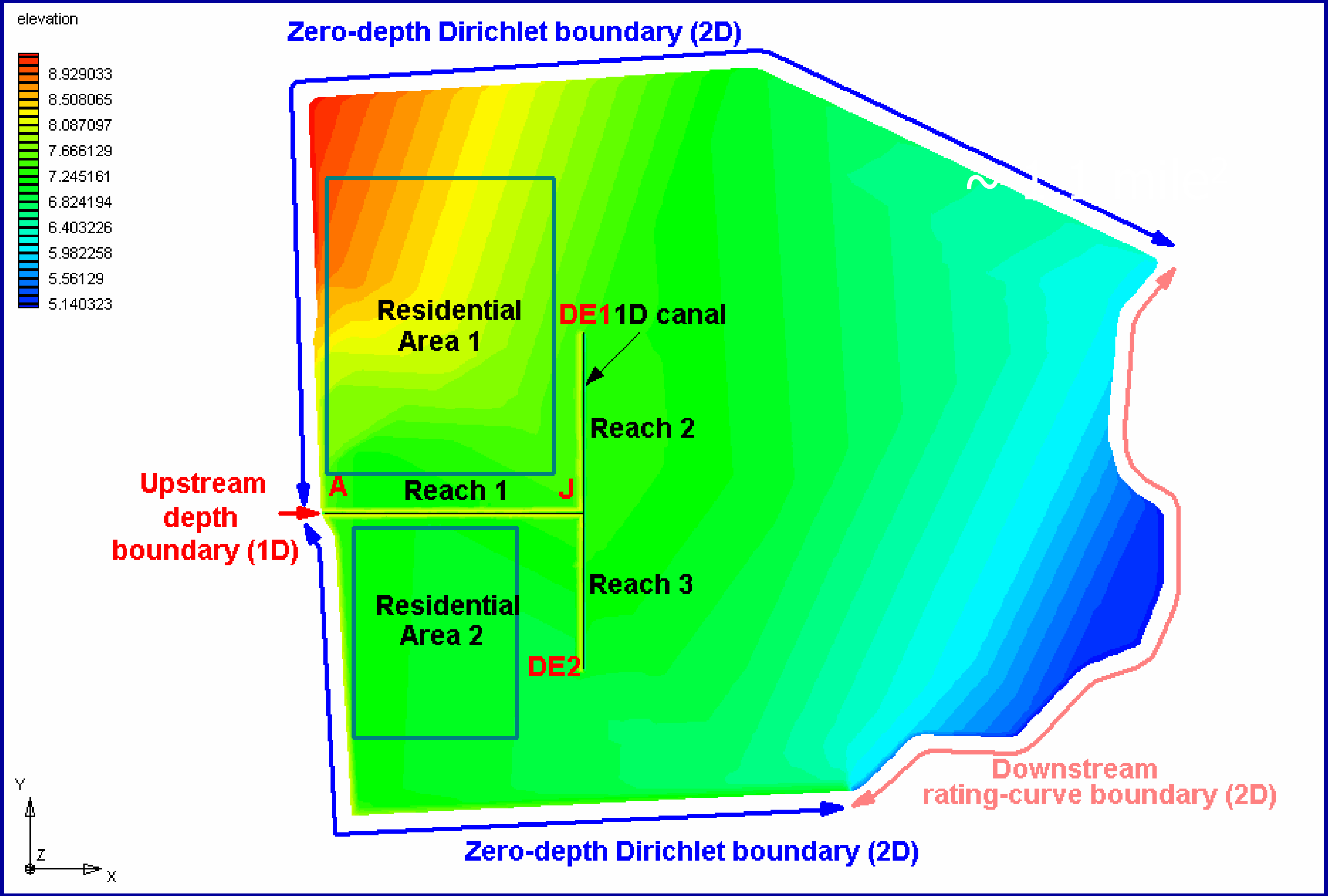
Examples of WASH123D Field Applications

- C-111 Spreader Canal (C-111SC) Design
- Biscayne Bay Coastal Wetland (BBCW) Watershed Systems
- Reservoir and Stream-River Network Modeling in Northern Palm Beach County

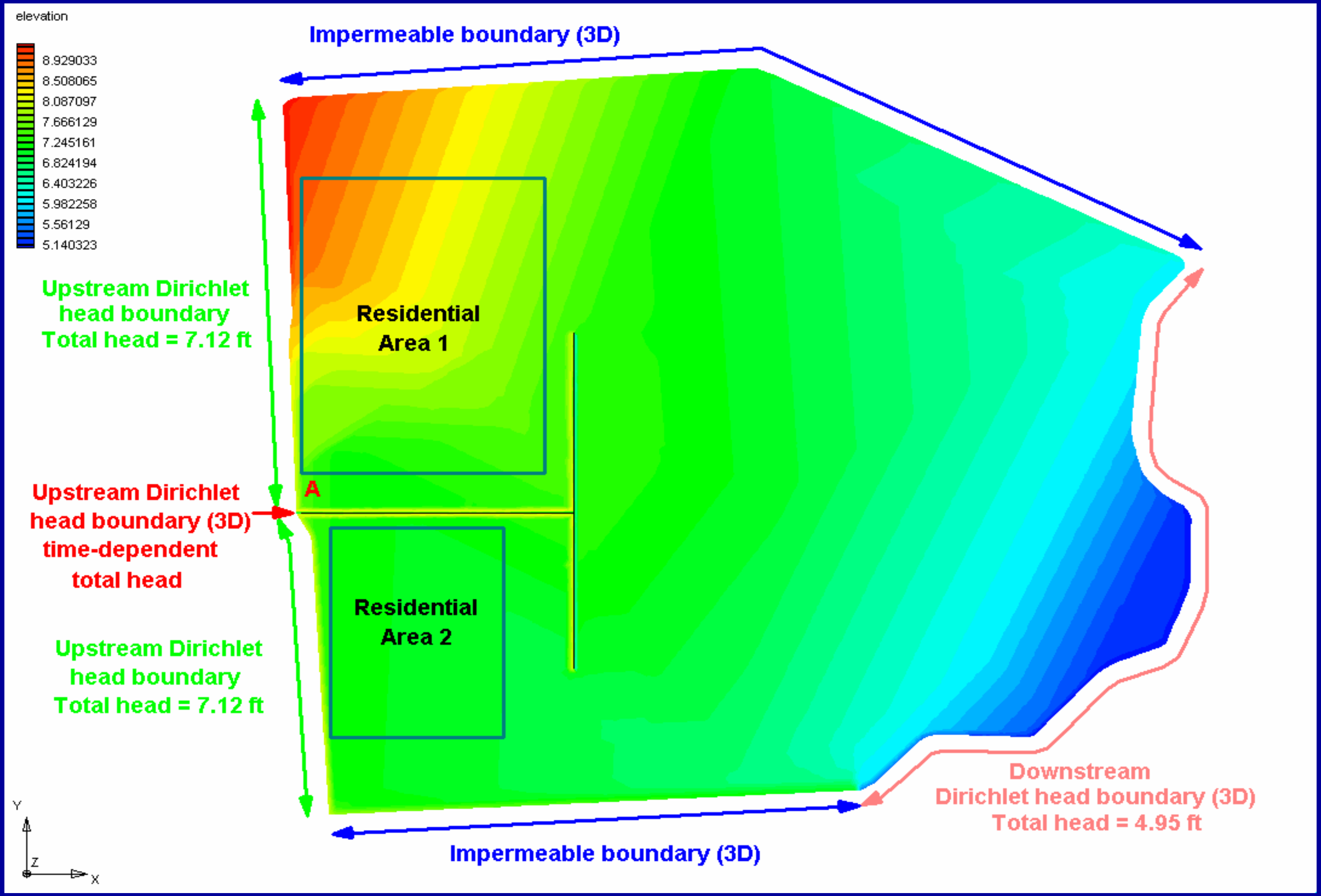
Example No. 1: C-111 Spreader Canal (C-111SC) Design



Surface Water BCs

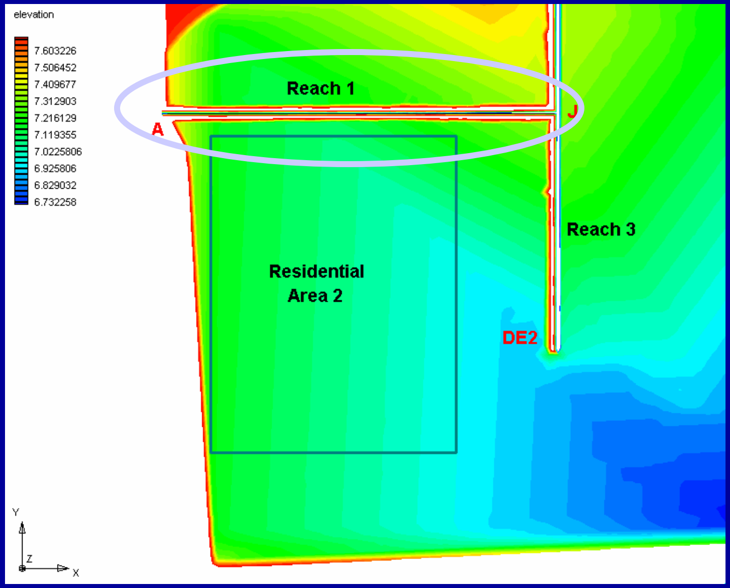


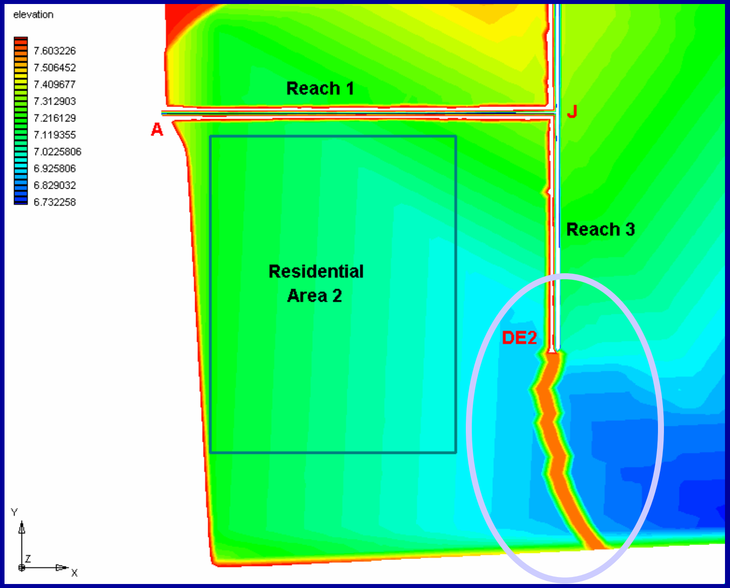
Subsurface Water BCs



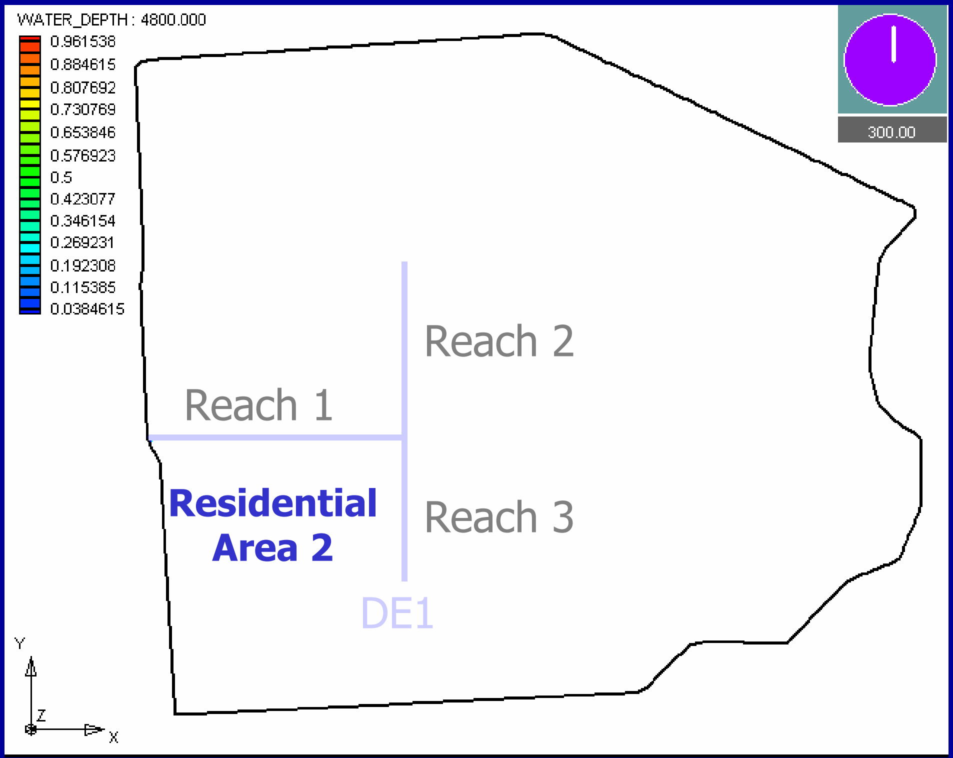
Design Scenarios

Case 1 (base case)	Case 2	Case 3
No liner in Reach 1 No extended levee	Liner in Reach 1 No extended levee	Liner in Reach 1 Extended levee applied

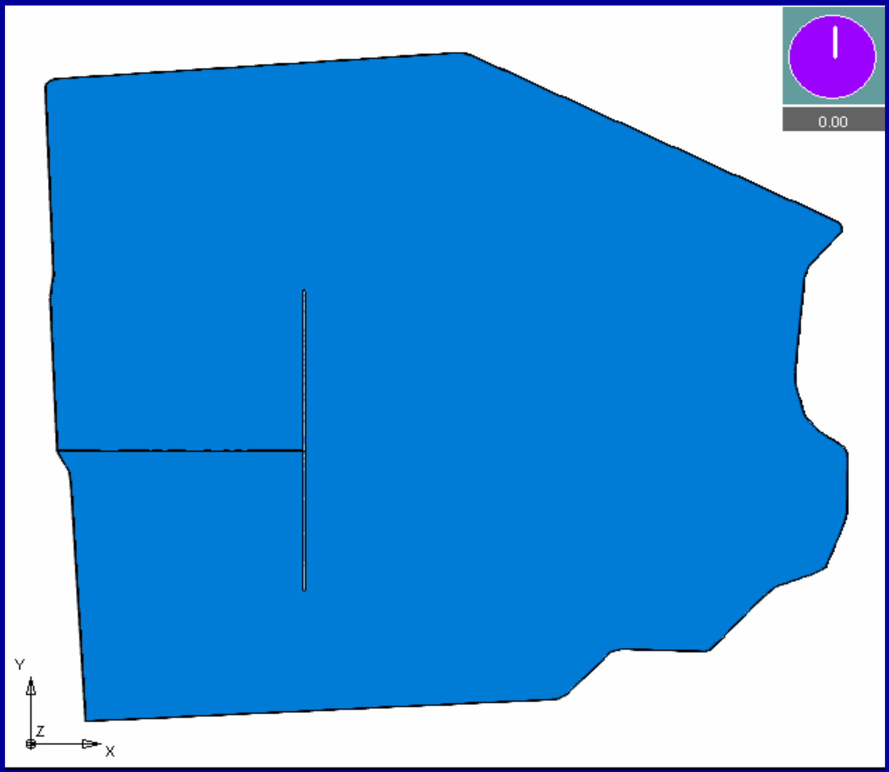




Case 1 (Base): DE_1_wd.avi and DE_1_wt.vi

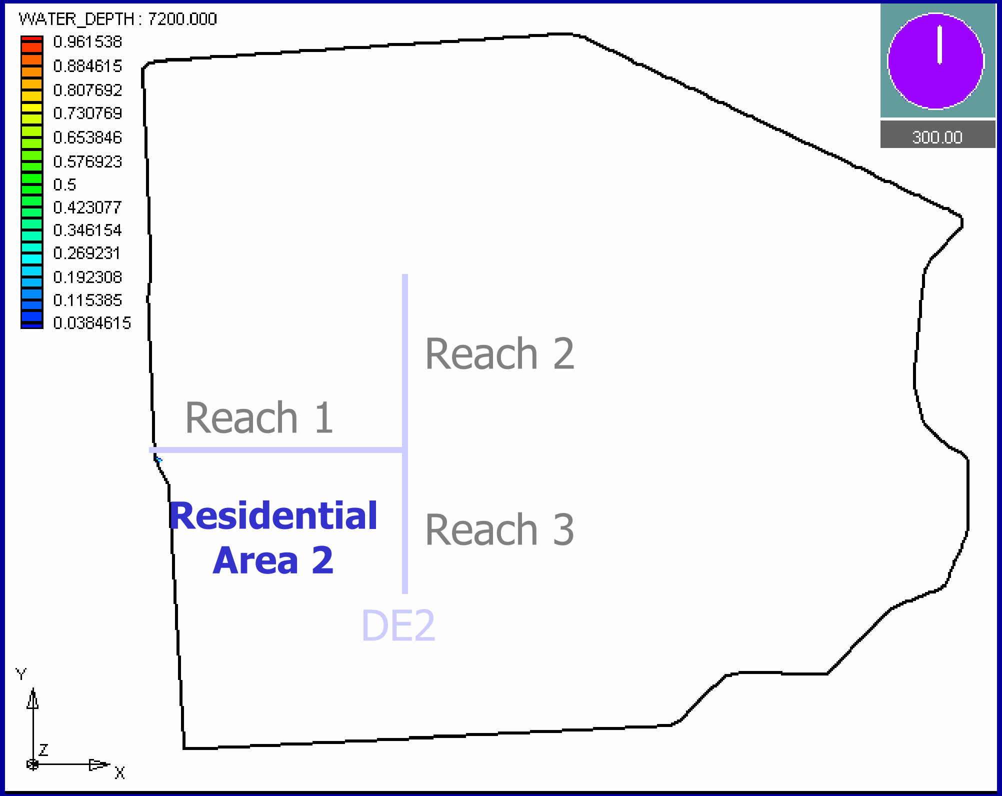


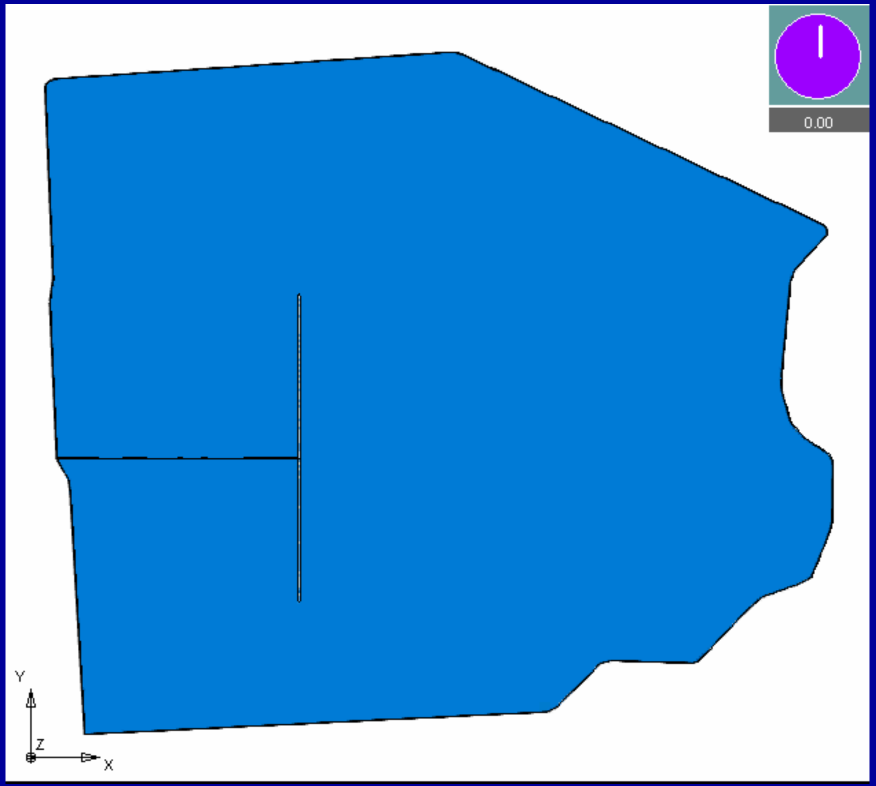
Overland Water Table



Groundwater Table

Case 2 (Liner) : DE_2_wd.avi and DE_2_wt.vi

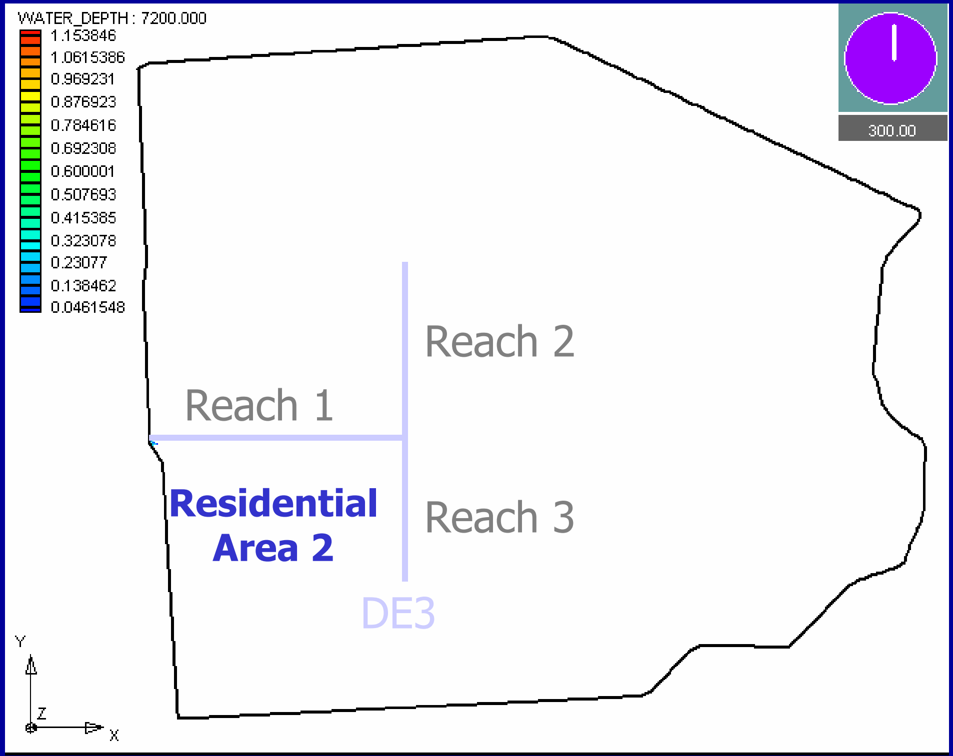




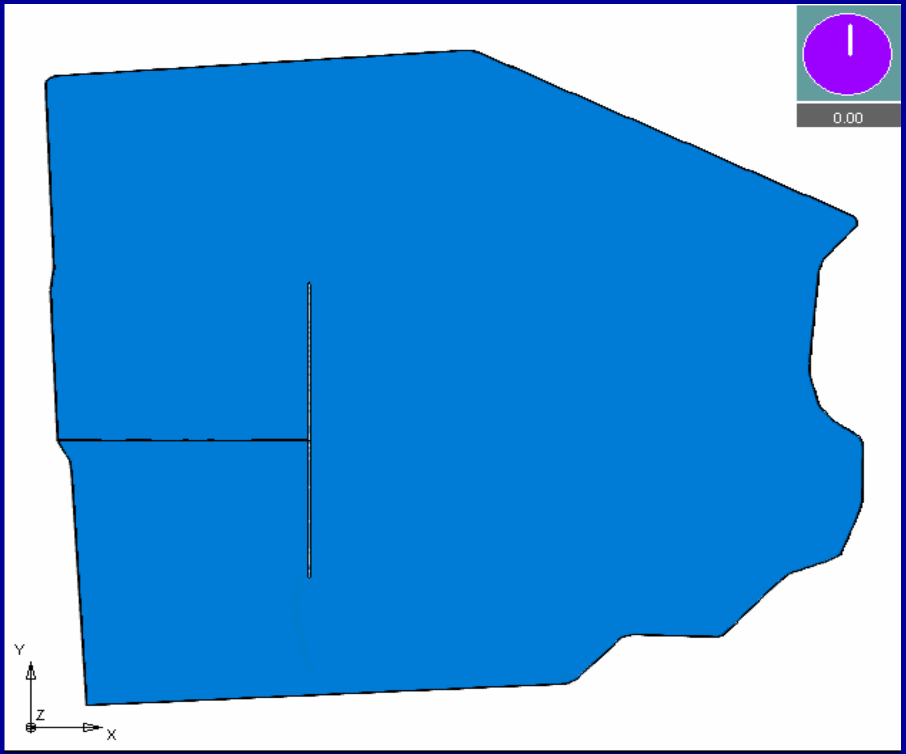
Overland Water Table

Groundwater Table

Case 3 (Liner+ Extended Levee) : DE_3_wd.avi and DE_3_wt.vi



Overland Water Table



Groundwater Table

Example No. 2: Biscayne Bay Coastal Wetland (BBCW) Watershed Systems

- The Biscayne Bay Coastal Wetland (BBCW) Project is one of more than 60 projects included in the federally approved Comprehensive Everglades Restoration Plan and has a ultimate goal to restore or enhance freshwater wetland, tidal wetland, and near shore bay habitat. The primary purpose of the BBCW project is to redistribute runoff form the watershed into the Biscayne Bay, away from the canal discharge that exists today and provide a more natural and historical overland flow through the existing and or improved coastal wetlands.
- The modeling effort to restore the wetlands includes modeling approaches, builds hydro-geologic conceptual model, selects model domain and boundaries, and calibrates model parameters. Discussions of calibration and preliminary results are given.
- WASH123D (v2.0) is used to develop the BBCW flow model. This flow model conceptualizes the BBCW watershed as a combination of 1D canal network, 2D overland flow regime, and 3D subsurface media.

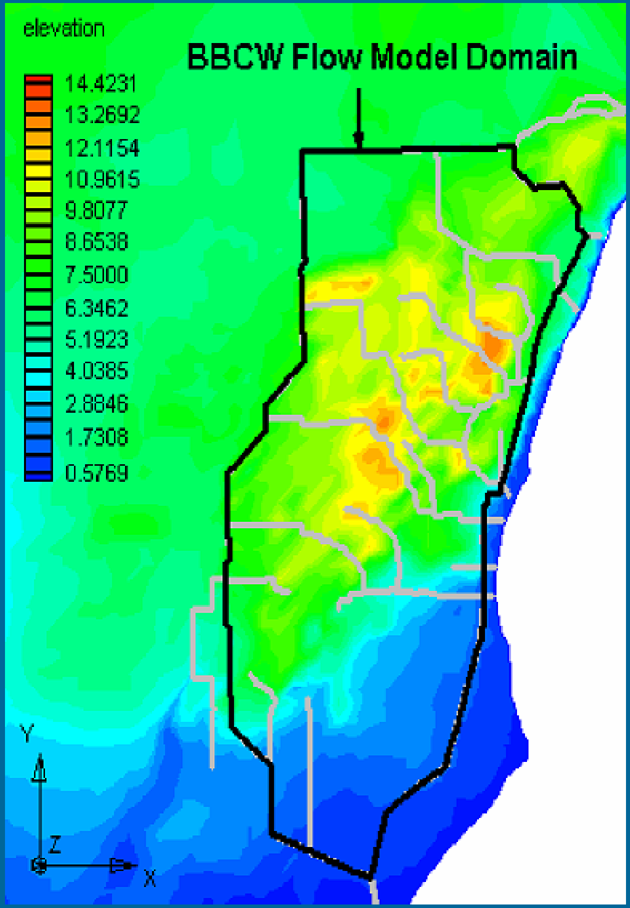


Figure 1. BBCW Project Area

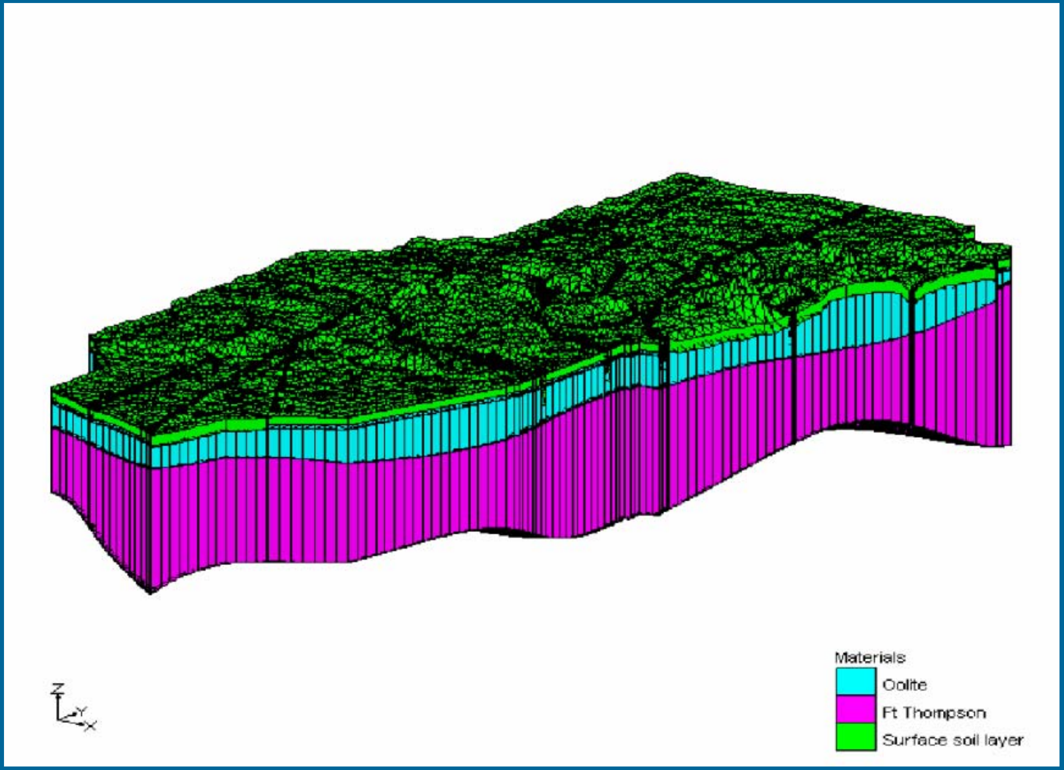


Figure 2. Solid Model for the BBCW Project Area

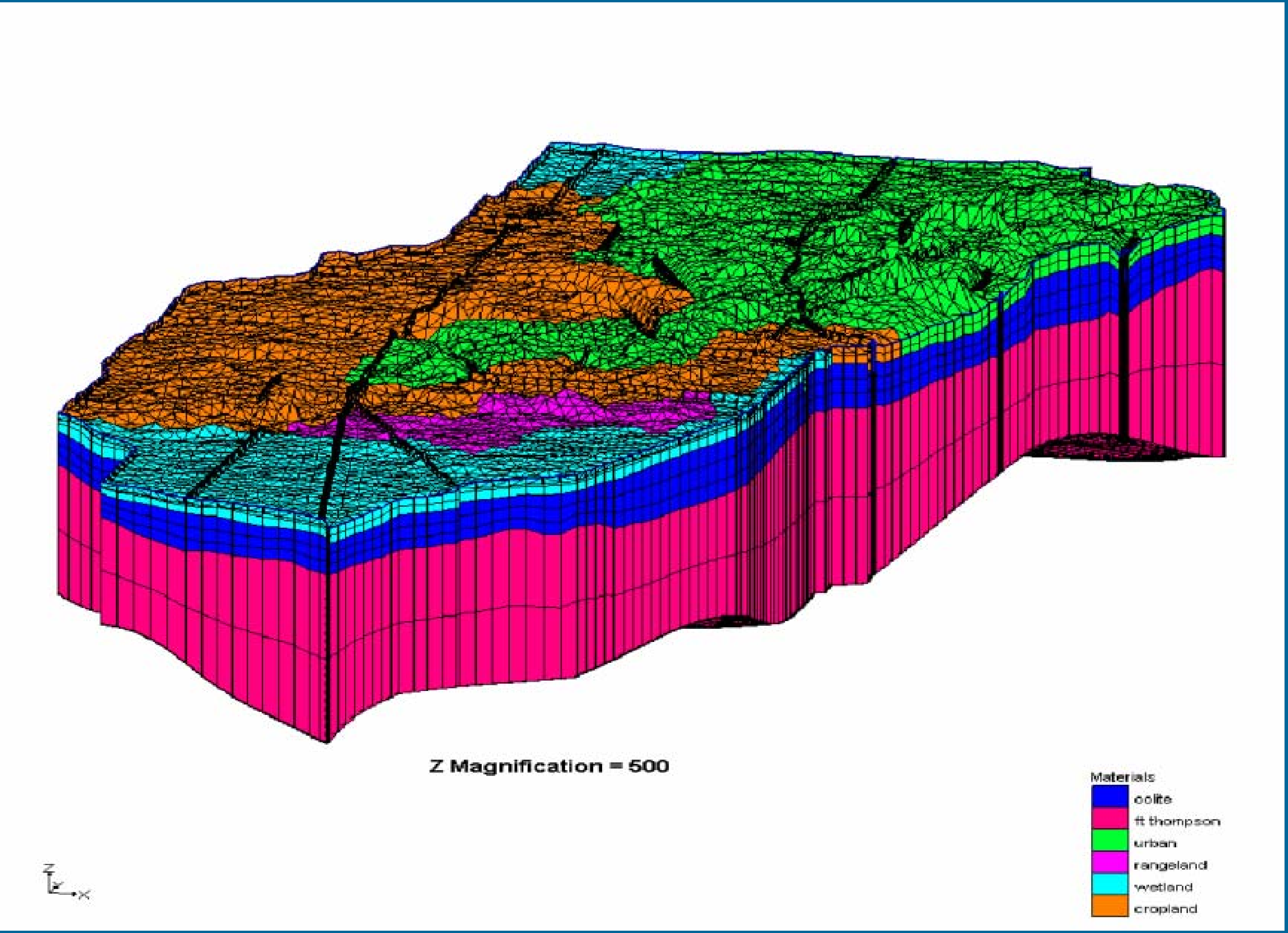


Figure 3. Computational Mesh (2D nodes = 8,339; 2D elements = 16,388; 3D nodes = 66,712; 3D elements = 114,716)

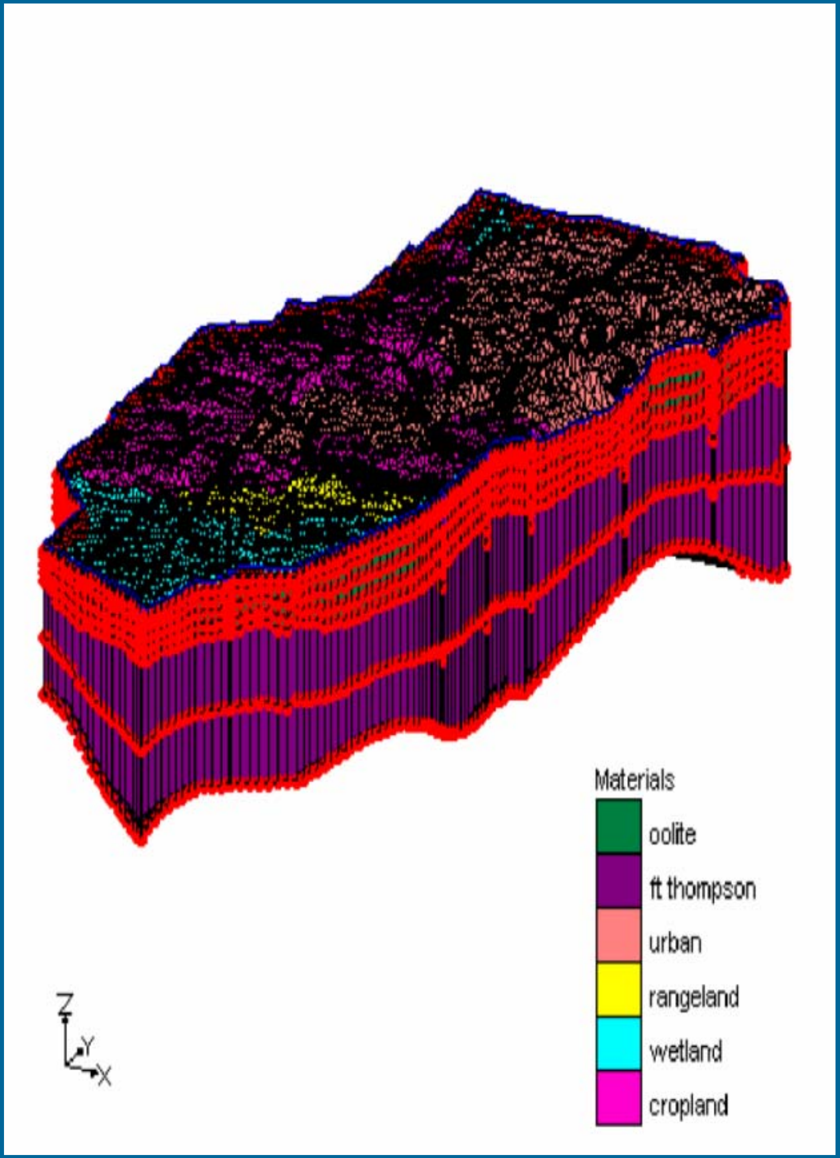


Figure 4. 3D Boundary Conditions

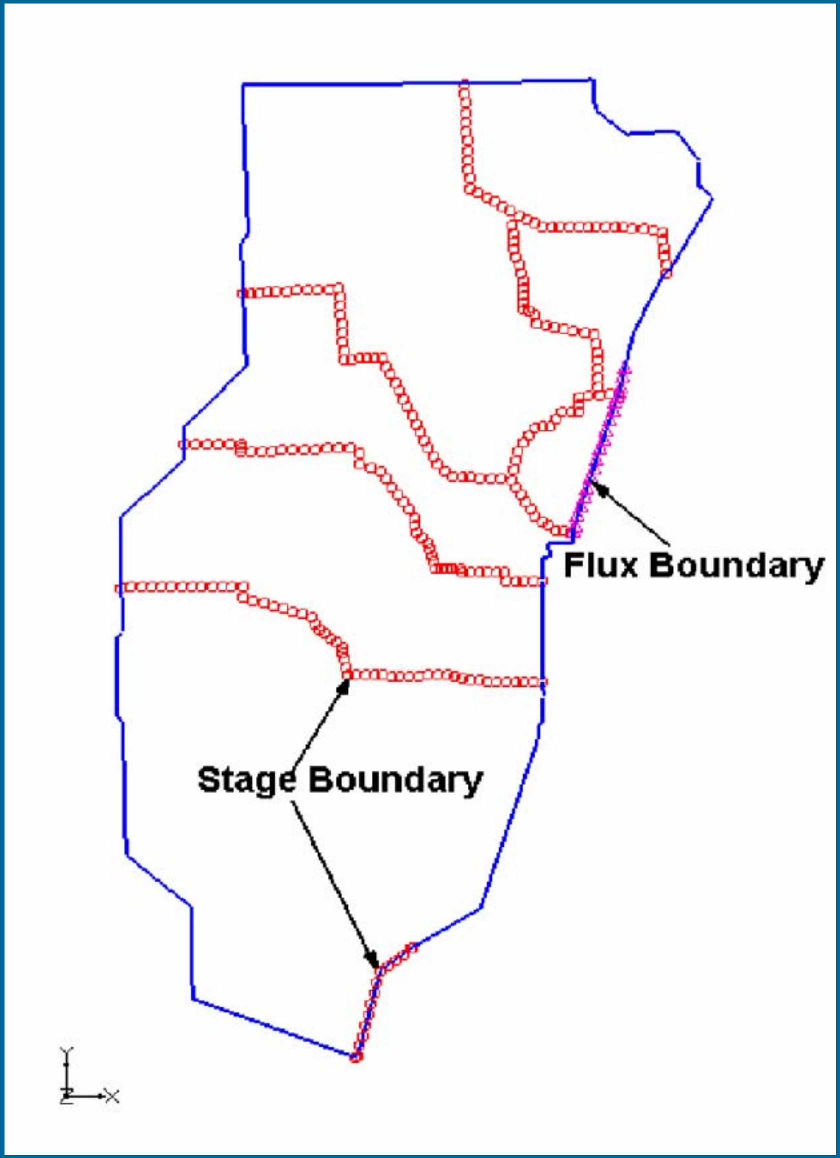


Figure 5. 2D Boundary Conditions

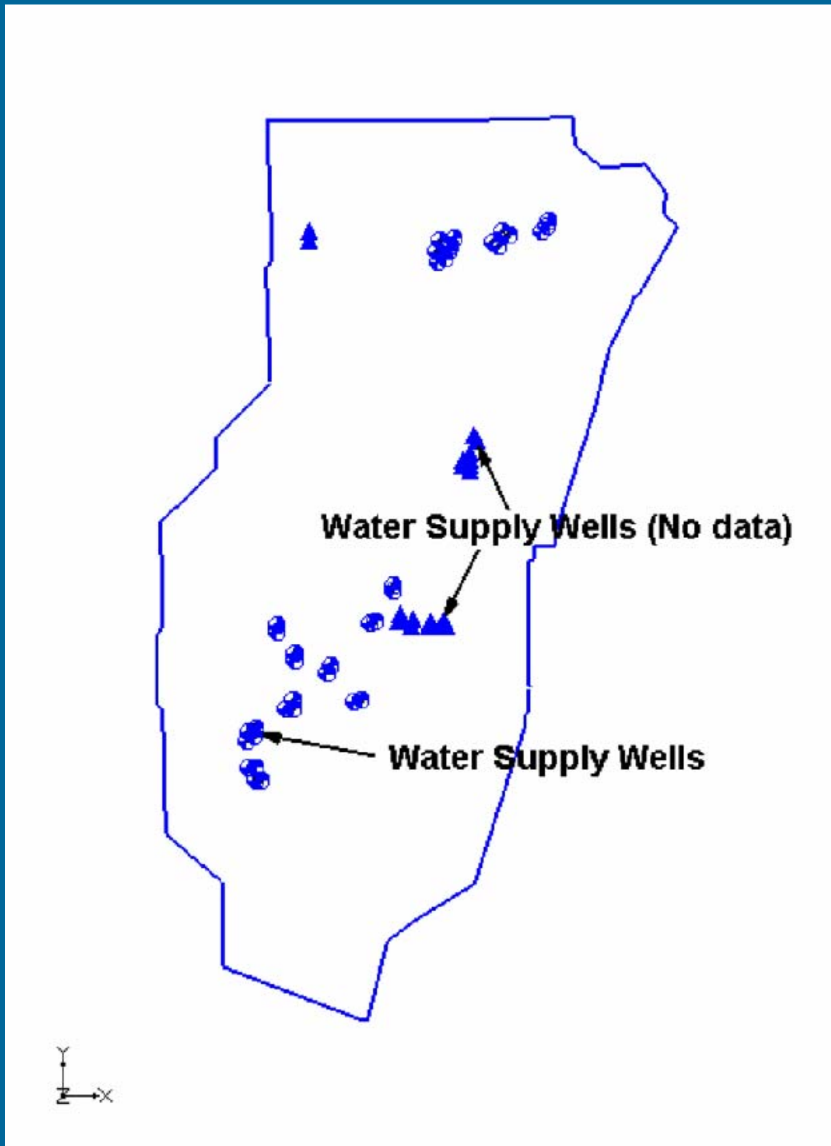


Figure 6. Locations of Pumping Wells

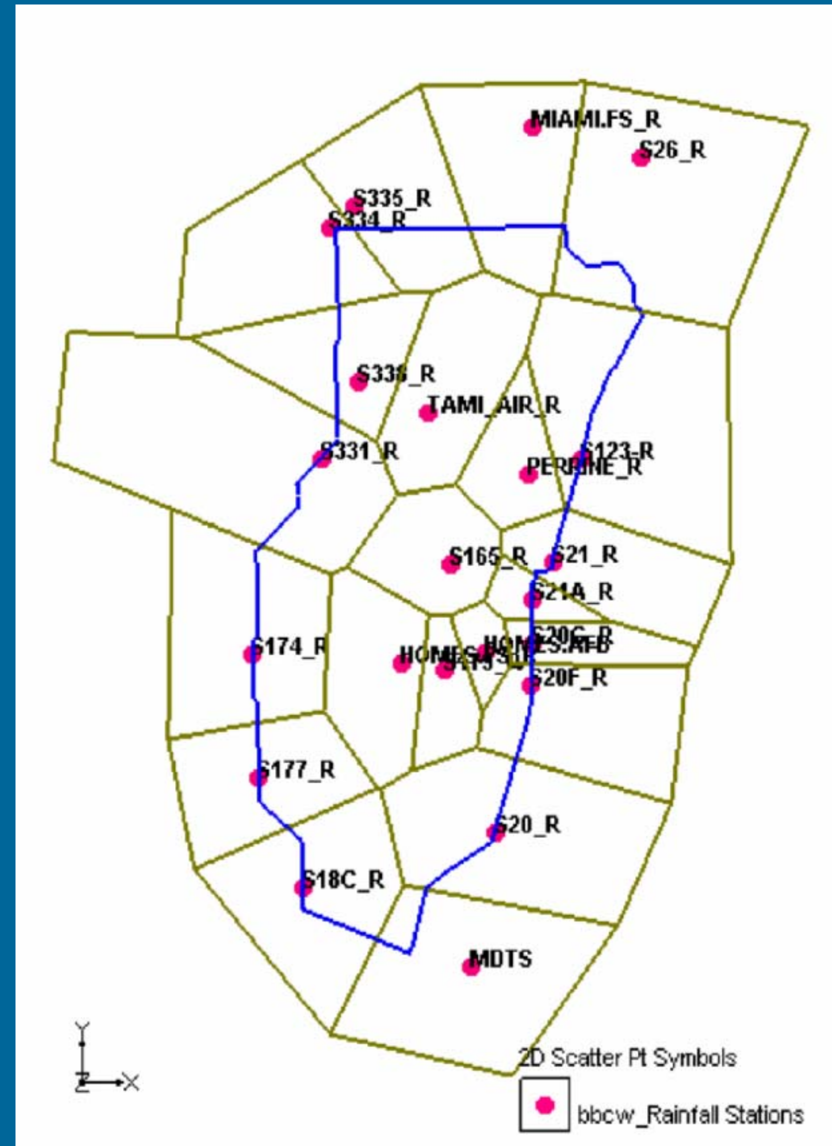


Figure 7. Locations of Rain Gages

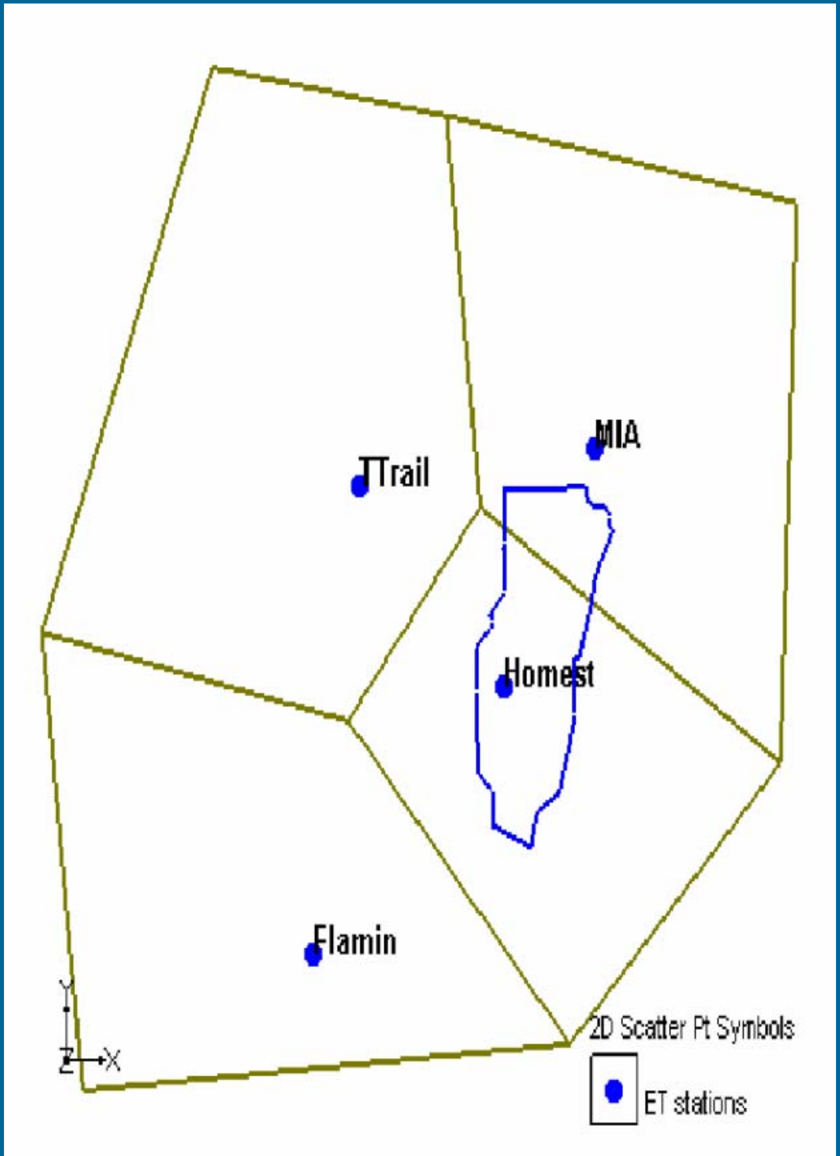


Figure 8. Locations of ET Gages

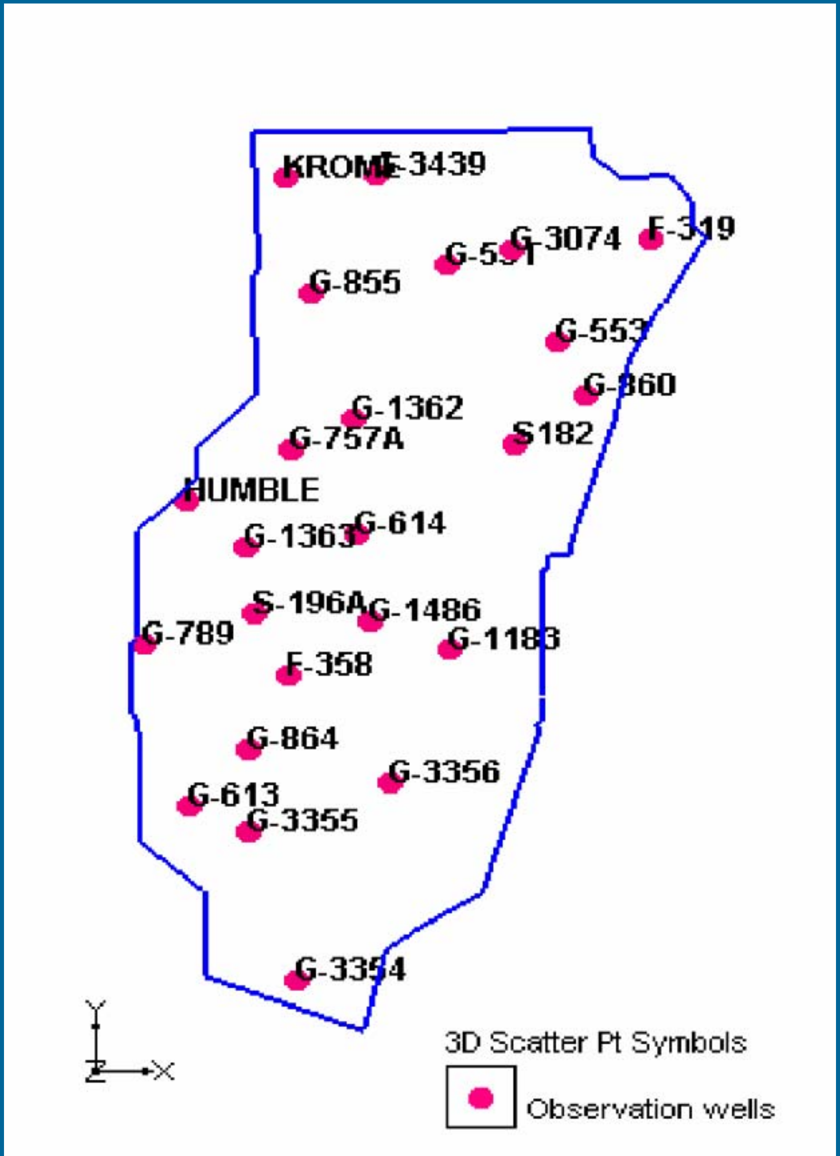


Figure 9. Locations of Observation Wells

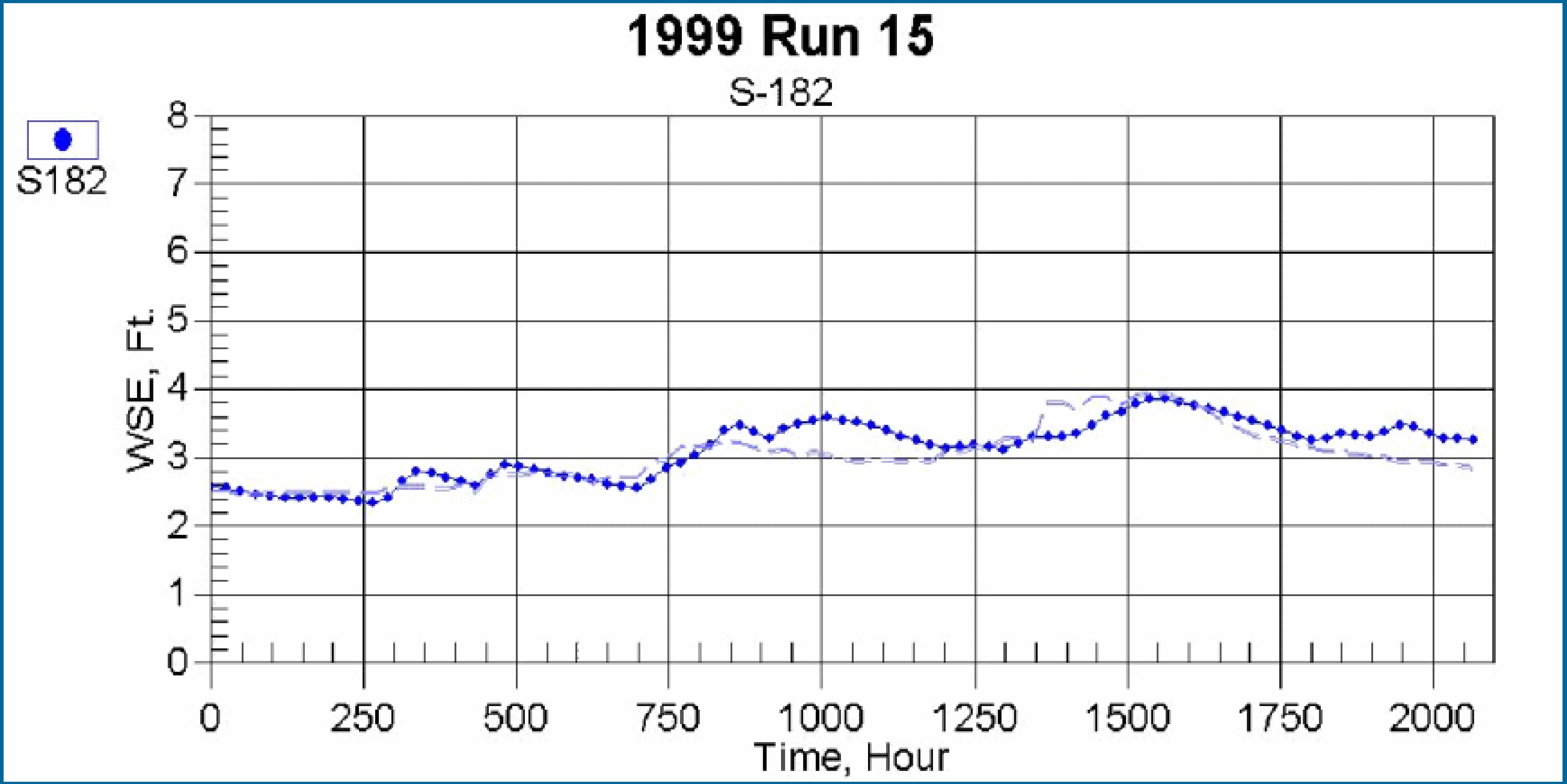


Figure 10. Results in East Coastal Ridge Area (S-182)

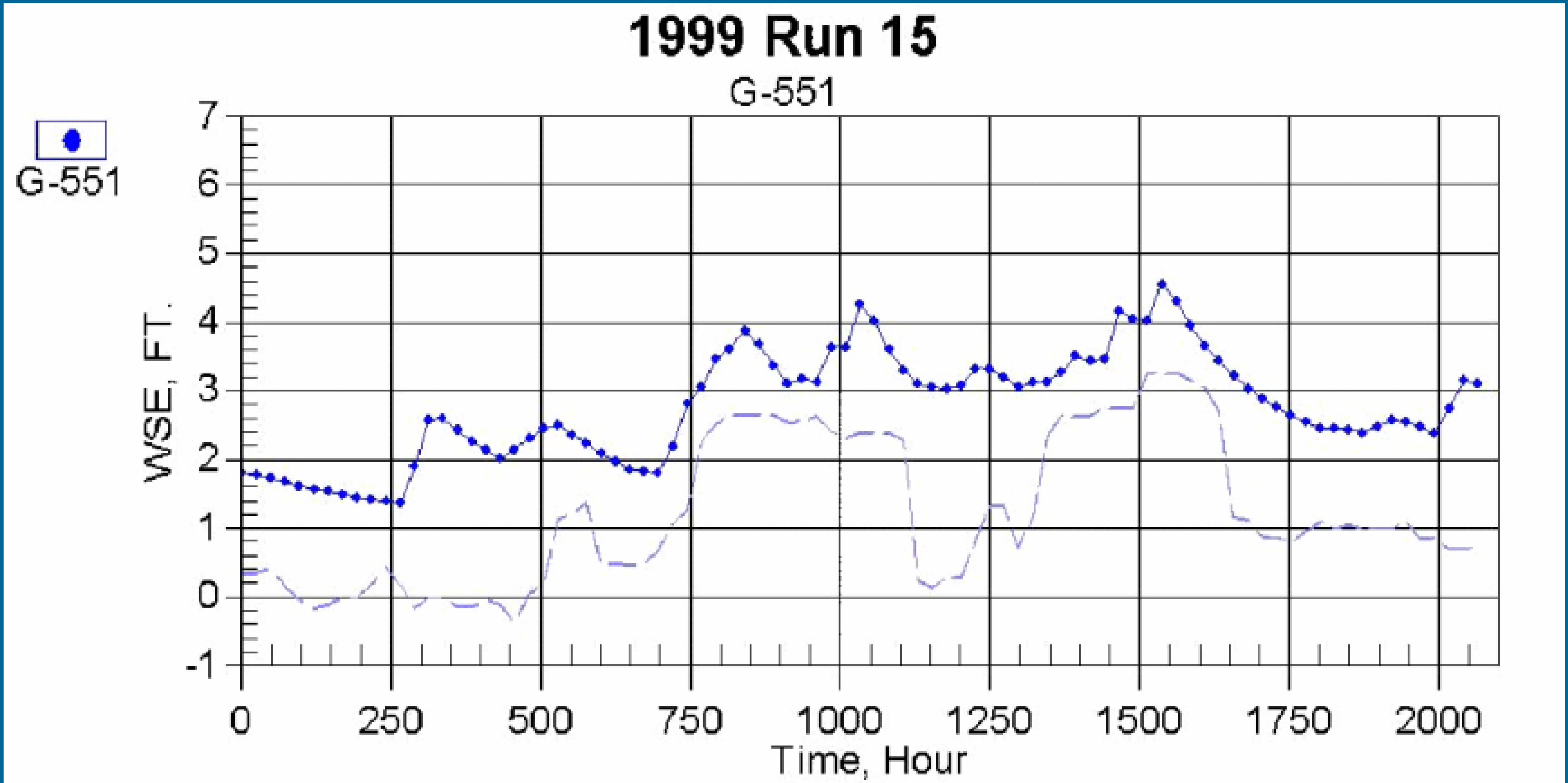


Figure 11. Results in the Water Supply Wells (G-551)

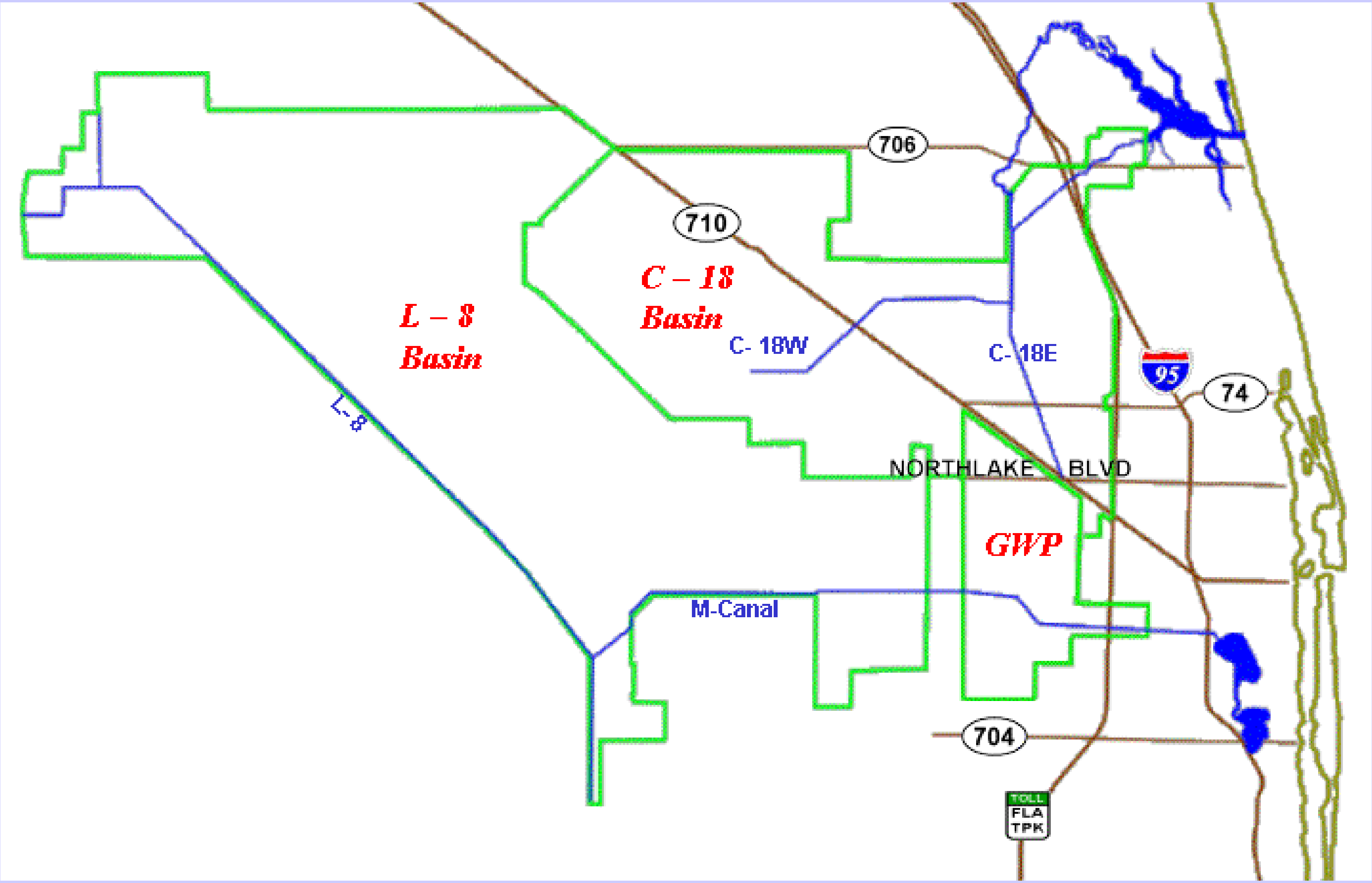
Figure 12. Results in the East of Homestead Airport (G-1363)

Figure 13. Results in the Model Land Area (G-3354)

- **Figures 10-13 indicate that the model responds well to the observed stage fluctuations and the computed stages are sensitive to the rainfall events as comparison to observed stages.**
- **Further investigation is needed to reduce the magnitude of stage fluctuations**
- **Figure 11 shows the computed stages near the water supply wells.**
- **Run time on 16-processors HPC machine (SC40) for 6 month simulation is about 3 days.**
- **SUMMARY Modeling South Florida watersheds with a physics-based computational model is a challenged task. The WASH123D model requires a graphical user interface (GMS 5.0) to generate a conceptual model, assign boundary conditions, and post-processes output.**

Example No. 3: Reservoir and Stream-River Network Modeling in Northern Palm Beach County

- The Reservoir Model and the River Model are two major components of WASH123D. The reservoir module takes an approach of water and energy budget, in which evaporation and transpiration modeled, not inputted.
- The Reservoir Model and the River Model were used for hydraulic modeling of surface water storage areas and canal networks in the study area of northern Palm Beach County.
- The canal system is composed of the L-8 Canal, the M-Canal, and the East and West Branches of C-18 Canal. The surface water storage areas include a number of reservoirs within the study area.



Study area boundary and local roads and landmarks

- Many internal and external boundary conditions and pumping operations are included as shown here and the next slide.

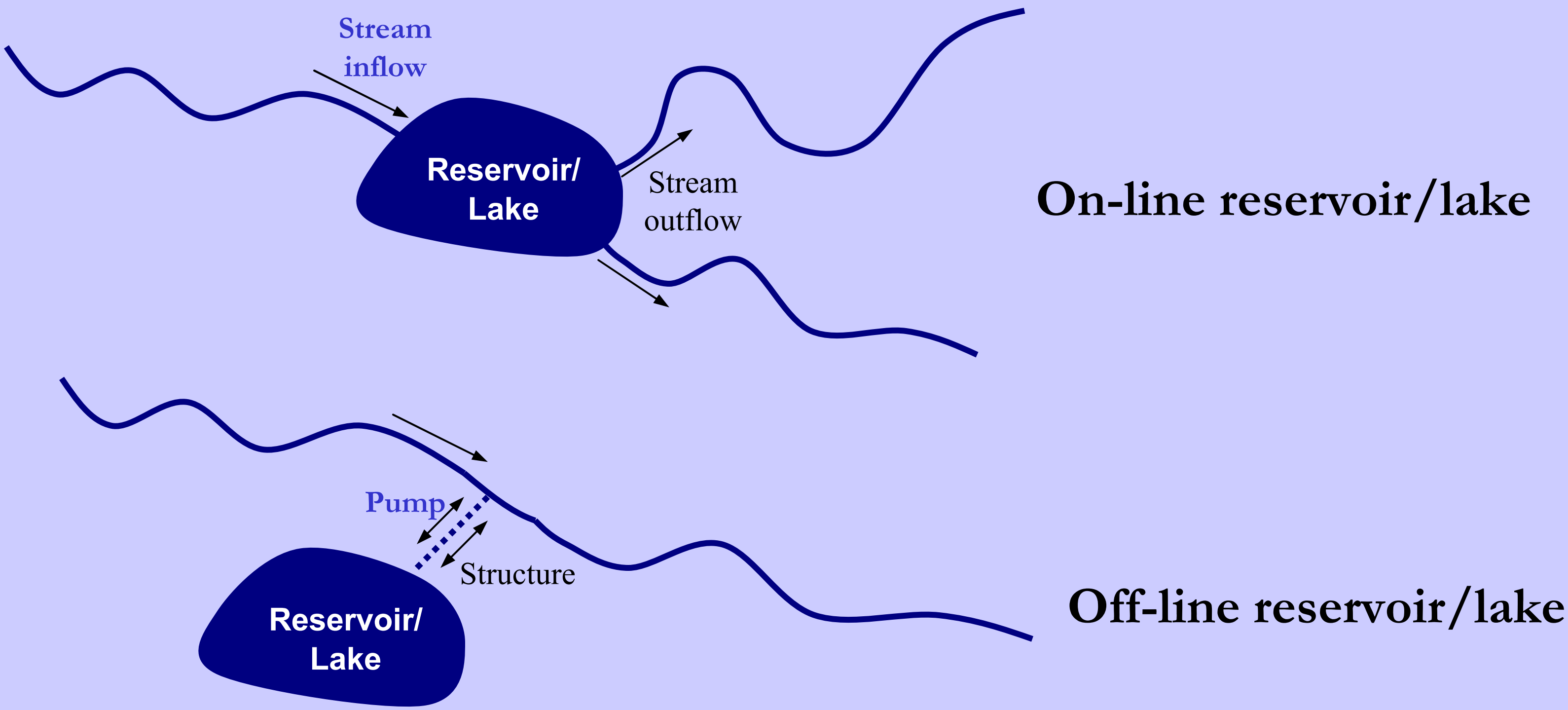
Internal Boundary Conditions

Internal Boundary	Description	Boundary Conditions
Weir	Represents one-dimensional flow transfer by weirs.	Discharge is determined by weir formula or rating curve of the weir.
Gate	Represents one-dimensional flow transfer by gates	Discharge is determined by gate formula or rating curve of the gate.
Culvert	Represents one-dimensional flow transfer by culverts	Discharge is determined by culvert formula or rating curve of the culvert.
Non-Storage Junction	Represents non-storage junctions of one-dimensional river branches.	Sum of discharge from all reaches at the junction equals to zero.

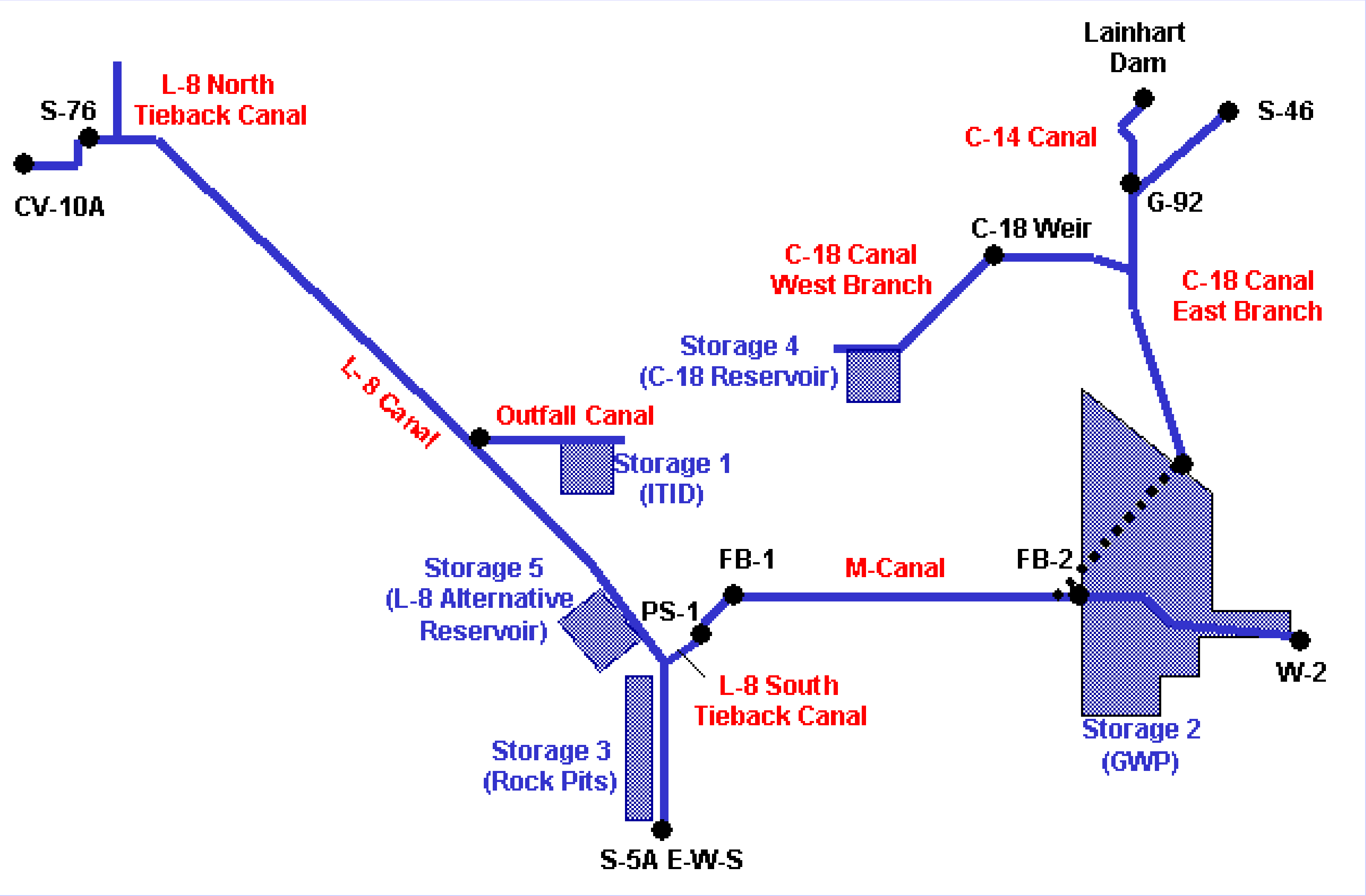
External Boundary Conditions

Boundary Type	Description	Boundary Conditions
Dirichlet	Water depth or stage is given at all time.	$h = h_B(t)$
Normal Flux	The volumetric flow rate is given at all time.	$Q = Q_B(t)$
General Rating Curve	The volumetric flow rate is given as a function of water depth or stage.	$Q = Q_B(h)$
Rating Curve of Elevation Controlled Gate	The volumetric flow rate is given as a function of water elevation and elevation controlled gate opening.	$Q = Q_B(h, Go(h))$
Rating Curve of Demand Controlled Gate	The volumetric flow rate depends on water elevation and demand controlled gate opening. The gate opening is given as a function water demanding discharge through the gate.	$Q = Q_B(h, Go(Q_D))$
Reservoir/ Lake	The river is connected to a lake/reservoir. It is used to couple the river flow with on-line reservoirs.	$H = H_R$

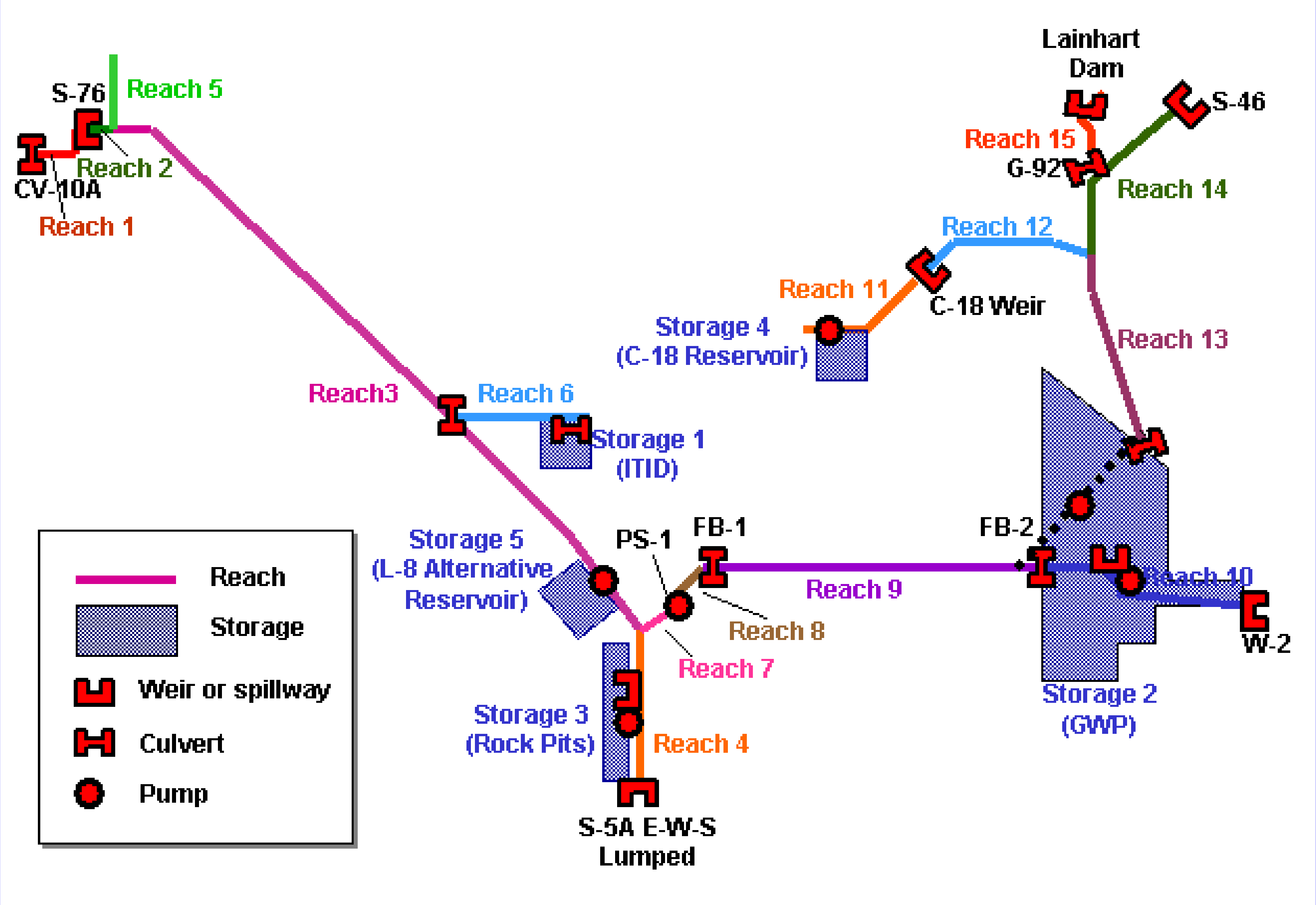
- The water transferred between these river and reservoirs is modeled by coupling of the 1-D model and the 0-D model. Two types of coupling between the River Model (1-D model) and the Reservoir Model (0-D model), the on-line coupling and the off-line coupling, can be identified and described in subsequent subsections.



On-line and Off-line Reservoirs/Lakes



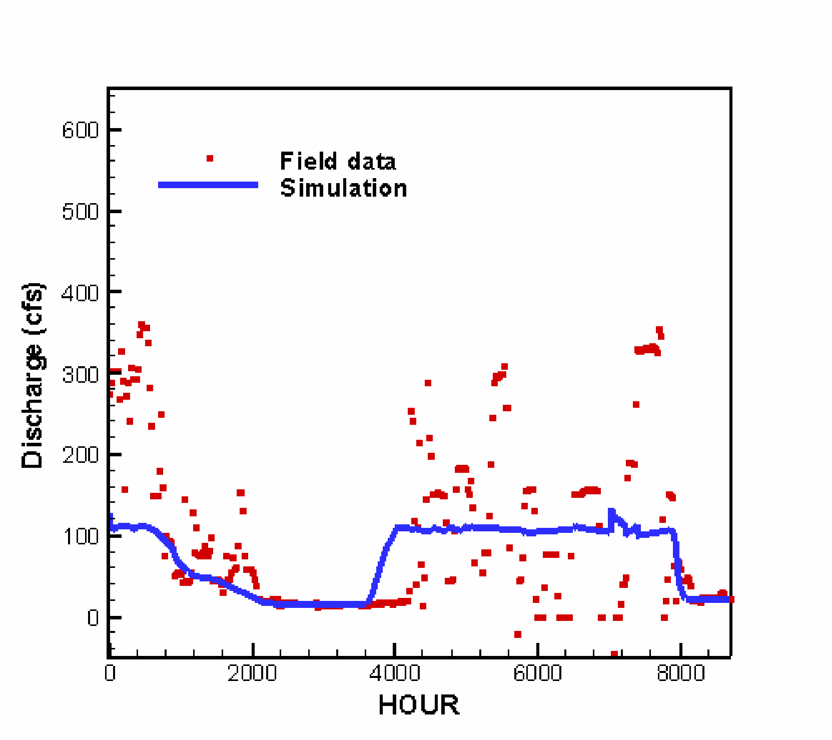
Model layout of Northern Palm Beach County: Storage Values



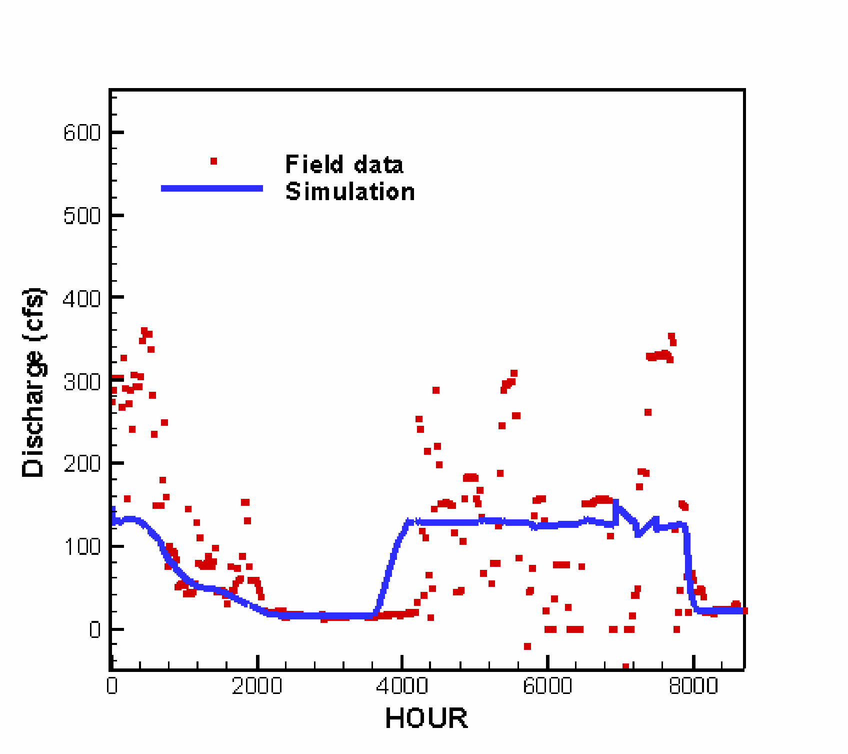
Canal Reaches in the Model

- **The object of the calibration is to match the cumulative discharge and the base flow at structure G92.**

Cumulative flow through different structures			
	Cumulative Flow through the Following Structures (acre-feet) (1/1/95 -12/31/95)		
	S-46	G-92	Lainhart Dam
Field Data	124230	59091	N/A
A	111795	52980	70507
B	104770	60027	77555

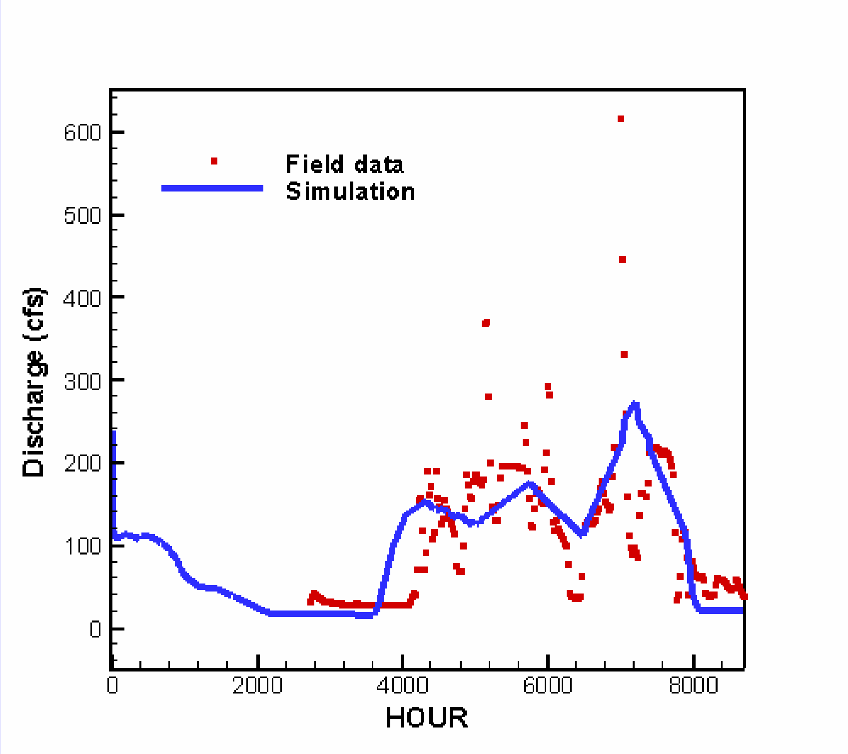


Case A

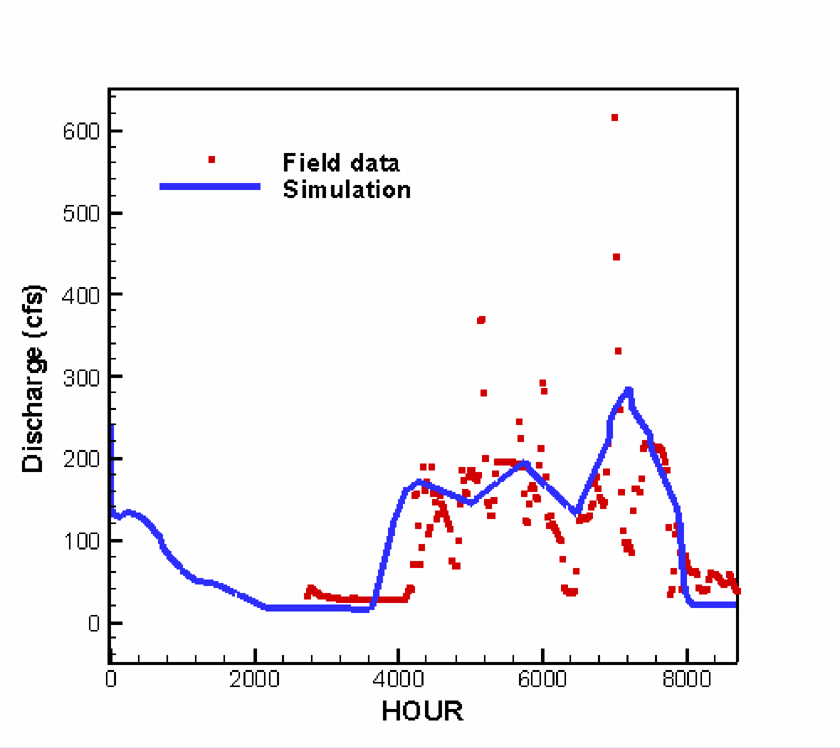


Case B

Hydrograph at structure G-92 from 1/1/95 through 12/1/95



Case A



Case B

Hydrograph at Lainhart Dam from 1/1/95 through 12/1/95.

- **After successfully calibrate the model, various combinations of proposed reservoirs were investigated.**
- **The modeling of WASH123D coupled with an economic evaluation resulting in the recommendation of $2,500 per acre-ft of storage, which was in contrast to earlier studies, which estimated a cost of $5,500 per acre-ft.**
- **The study saved FDEP of approximately $250 millions for the management.**

Conclusions (1)

WASH123D has taken a step beyond previous models.

- Physics-based fluid flows in stream/river network, overland regime, and subsurface media are considered. Kinematic, diffusive, and fully dynamic wave approaches are all included in dentric rivers and overland regime. Richards equation is employed for subsurface flow.
- Junctions and control structures including weirs, gates, culverts, levees, pumping, and storage ponds are included to facilitate management.
- Boundary conditions for junctions and internal structures are implemented to explicitly enforce mass balance.
- Interface boundary conditions are rigorously dealt with by imposing the continuity of fluxes and the continuity of state variables or the formulation of fluxes when the state variables are discontinuous.
- The model can be applied to large scale problems (e.g., watershed flooding, groundwater-surface interactions) as well as small scale problems (e.g, dam breaks).

Conclusions (2)

- The model has been applied to real-world applications in the management and restoration of hydroplane.
- WASH123D could be applied to
  - Design of flood protection works
  - Design of wetlands and water conservation areas
  - Impact of tropical storms on flooding
  - Deep injection of fresh water for future use
  - Dredge material disposal facility design
  - Hazardous and toxic waste remediation
  - Wellhead protection area definition
  - Environmental restoration plans